TABLE OF CONTENTS - Appendix H

LIST OF FIGURES

LIST OF TABLES

This page intentionally left blank.

Appendix H
INTERIM REPORT ON EVOLUTION OF WTC FIRES, SMOKE, AND DAMAGE BASED ON IMAGE ANALYSIS

H.1 COLLECTION AND ANALYSIS OF VISUAL MATERIAL

Photographic and video images of damage and fires in the World Trade Center (WTC) towers and WTC 7 are critical for guiding the investigation led by the National Institute of Standards and Technology (NIST). The conditions of the towers immediately following the plane strikes, the rates of fire development and spread through the buildings, and indications as to the floors on which the structural collapses may have begun and their causes are examples of issues that are being addressed using imagery. Observations discussed below demonstrate the importance of such visual evidence.

This appendix is designed to provide an update on NIST efforts to collect and analyze visual material available for the WTC disaster. This effort is part of Project 5, Reconstruction of Thermal and Tenability Environment, and this is the focus of the material presented. It is important to recognize that the effort is coordinated with the other projects that form the NIST-led WTC Investigation, and the visual material is being used as the basis for additional analysis in these projects.

The amount of visual material recorded on September 11, 2001, was extraordinary. The terrorist attacks occurred in an area that is the national home base of several news organizations, has several major newspapers, and is the center of the fashion industry. As a result, there were likely hundreds of professional photographers and videographers equipped with excellent equipment and the knowledge to use it in the immediate area. New York City is also a major tourist destination, and visitors often carry cameras to record their visits.

The WTC towers (WTC 1 and WTC 2) were immense, and they dominated the New York City skyline. When WTC 1 was struck by American Airlines Flight 11 around 8:46 a.m., the approach of the plane was captured by at least two videographers who were coincidentally filming nearby. Other photographers and videographers in the vicinity began recording within a few seconds of the impact. As fires grew in the tower, smoke pouring from the building formed a plume that could be seen for miles in all directions in the clear air of September 11, 2001. People in Manhattan, Brooklyn, Queens, and New Jersey began to turn their cameras toward the WTC complex. The major news organizations began coverage almost immediately and began moving professionals into position to cover the event. Numerous other videographers and photographers, both professional and amateur, started moving toward the WTC in order to create their own visual records.

At the time United Airlines Flight 175 struck WTC 2, around 9:03 a.m., the approach and collision of the aircraft were recorded by numerous cameras from a variety of directions. Many people continued to record images until WTC 2 collapsed, around 9:59 a.m. Following this collapse, the amount of visual material decreased markedly as people rushed to escape the area and the huge dust clouds generated by the collapse obscured the site. This situation was only exacerbated by the collapse of WTC 1, around

10:28 a.m. The visual record between the period following the collapse of WTC 1 and the collapse of WTC 7, around 5:21 p.m., is much less complete, but there is still a substantial amount of material.

Even as the disaster unfolded, it was clear that a large amount of visual material was being recorded that was being used to inform the public, demonstrate the immensity of the disaster, and to chronicle the associated human suffering. It is now clear that the imagery of September 11, 2001, is the most extensive ever recorded of such a single tragic event. The resulting visual record offers an unparalleled opportunity to contribute to the technical understanding of the tragedy of September 11. Even though it was clear that an extensive visual record of the events of September 11 existed, approaches for obtaining access to photographs and videos and cataloging the material had to be developed. These critical aspects of the task have required a great deal of time and effort.

H.1.1 Sources

Potential sources of visual material have been identified in a number of ways. Recordings of newscasts from September 11, 2001, and afterwards, documentaries and other remembrances, provided information directly, but also pointed toward other potential sources of material. The major photo clearinghouses, such as AP, Reuters, and Corbis, have World Wide Web sites that were reviewed for material related to September 11. Several members of the media suggested sources. Several collections of visual material have been assembled for charitable or historical purposes. Collections from the *Here is New York City* exhibition and the *September 11 Digital Archive* were reviewed. Many photographs and videos began appearing on the Web as early as September 11. These could often be identified by Web searches, and in many cases contact information was provided. Public appeals for visual material were made during Investigation news conferences and updates. News accounts of these events led many to contact NIST using the toll-free number or the Investigation Web site. Frequently, a new source would provide information about other potential sources.

NIST hired a visual media consultant, Mr. Valentine Junker, to act as its representative in the New York City area. In addition to interacting with a number of individuals, his efforts were particularly valuable in interfacing with the major television networks and local New York City stations as well as the major photographic news services.

H.1.2 Procedures

The identification of sources was only the first step in the collection process. It was then necessary to contact the source, request the material, and make arrangements for its transfer. Special considerations such as copyright and privacy issues often needed to be addressed. Once an agreement was reached, arrangements were made to review and transfer copies of the material to NIST.

In the collection process, emphasis has been placed on obtaining material in a form that is as close as possible to the original in order to maintain as much spatial and timing information as possible. In the case of digital photographs and videos this implies a direct digital copy. For film or slide photographs, it would be a high-resolution digitized version of the original media, and for analog video, a direct copy from the original source. While it was not always possible to maintain this standard, the majority of material ultimately collected was handled in this manner.

H.1.3 Contents

Significant progress has been made in collecting visual material related to September 11, 2001. Thus far, in excess of 150 hours of video have been assembled. At the time of preparation of this update, video footage has been provided by NBC, CBS, ABC, CNN and local New York City stations WABC, WCBS, WNBC, WPIX, WNYW and New York City One. In many cases, the videos provided not only include material broadcast (known as air checks), but also material that was recorded but not broadcast (known as outtakes). Additionally, videotapes recorded by more than 20 individuals have been received.

Photographs have been provided by a number of sources dominated by commercial photo services, the New York City Police Department (NYPD), the New York City Fire Department (FDNY), and individuals. Well in excess of 6,000 photographs, representing more than 185 photographers, have been received. Professional news organizations that have provided material include AP, Corbis, Reuters, the *New York City Times*, the *Daily News*, and the *Star Ledger*. As for the videos, many of these organizations have provided access to unpublished photographs. The majority of photographs have come from individual photographers, both professional and amateur.

It is difficult to estimate the actual amount of relevant visual material recorded on September 11, 2001, and thus to estimate how complete the collection efforts have been. There is certainly material that has not been identified and collected. However, NIST believes that the extraordinarily large collection of video material that it possesses is sufficient for the Investigation.

H.2 DATABASING AND CATALOGING

It would be impossible to effectively use the vast amount of visual material collected for the Investigation without some means of organizing and cataloging the material.

H.2.1 Digital Storage

Very early in the task, the decision was made to save all material in digital format on large digital data storage devices. This approach has several advantages. Because the material is in digital form, it can be assessed quickly. It is not necessary to search for a particular photographic collection or videotape, and no special equipment is required to display it. Because most material is received in other forms, the digital storage is in effect a backup system for the original. Additional redundancy is provided by backing up the entire digital storage system at regular intervals. Because videos are saved digitally, they can be analyzed using a variety of commercially available editing software.

Various storage solutions were considered. An approach was finally adopted in which a central server along with two 325 gigabyte and one 160 gigabyte external hard drives were connected with eight personal computers equipped with 70 gigabyte hard drives. The personal computers not only provide additional disk storage, but also serve as workstations for data entry and analysis. All of the systems are connected by high-speed ethernet to form a single network configured such that the entire system becomes, in effect, a single mass storage device. The total amount of storage available is roughly 1.4 terabytes.

Due to security concerns related to the sensitive nature of some of the visual material and copyright issues, the computer network has been set up with its own dedicated connections and is isolated from the internet backbone of NIST. Policies have been adopted that require all viewing and analysis of the material to be done in secured rooms using secured networks.

H.2.2 Digitizing Techniques

When new visual material is received at NIST, it is stored digitally on the dedicated system. If the material is already in digital form this simply means copying and saving it on the system. Analog material must be first digitized in some manner. For instance, a photograph might be scanned and digitized, or a video might be converted to a digital video format (typically mini-DV) and then copied to a hard disk.

Each arriving video is logged into VideoList, a Microsoft Access database written specifically for this application. There it is assigned a unique identification number. Pertinent information concerning the tape is recorded, including its duration, the network and broadcast date if applicable, its physical format (e.g., VHS, Hi-8, or mini-DV), where the tape is stored, whether the tape is an original or a copy, its source, whether it has been digitized, whether it contains embedded timecode, and general notes on its content. Figure H–1 shows an example of the entry sheet for the VideoList database. Videos to be stored digitally are copied onto mini-DV media, and each copy is also logged into the database. VideoList also contains a calculator for assisting in the calculation of clip timing that is described in H.3.1. Selected video material is then transferred to hard disk for storage. Video material is often found to have natural breaks, such as when the camera is turned off and on (e.g., by an individual videographer) or when multiple cameras are used (e.g., during a newscast). It is advantageous to treat each of these breaks as the end of an individual video. This is accomplished by a process known as "clipping." By using Adobe Premiere software and a personal computer to control the video player, it is possible to identify and note such breaks in a "clip file." The clip file can also contain notes related to the material. Once a clip file has been generated for an entire tape, the software goes through and automatically generates multiple data files containing the video material. The material is stored in "avi" format, which maintains all of the digital information. The maximum video file size that can be handled by this system is 1 gigabyte. This corresponds to slightly more than 4 1/2 min of avi video. Longer continuous video segments are broken into lengths having roughly this period. Breaking longer videos up in this manner also makes them easier to search and catalog.

H.2.3 Searchable Database

As noted earlier, a vast amount of visual material has been collected and saved digitally as part of the investigation. Without some organization, it would be impossible to use this material effectively. A commercial database program written specially for organizing visual material, Cumulus, was chosen for this purpose. This software is designed to collect individual "assets" in specified catalogs and to allow the assets to be characterized with a variety of attributes. It is possible to generate specific attributes and include these in specially designed forms for data entry. Once a catalog has been assembled, it is possible to search for assets having a specific attribute or combinations of attributes. Quite sophisticated searches can be created. It is also possible to order assets based on a particular attribute. As an example, when dates and times are assigned, the assets can be ordered in chronological order.

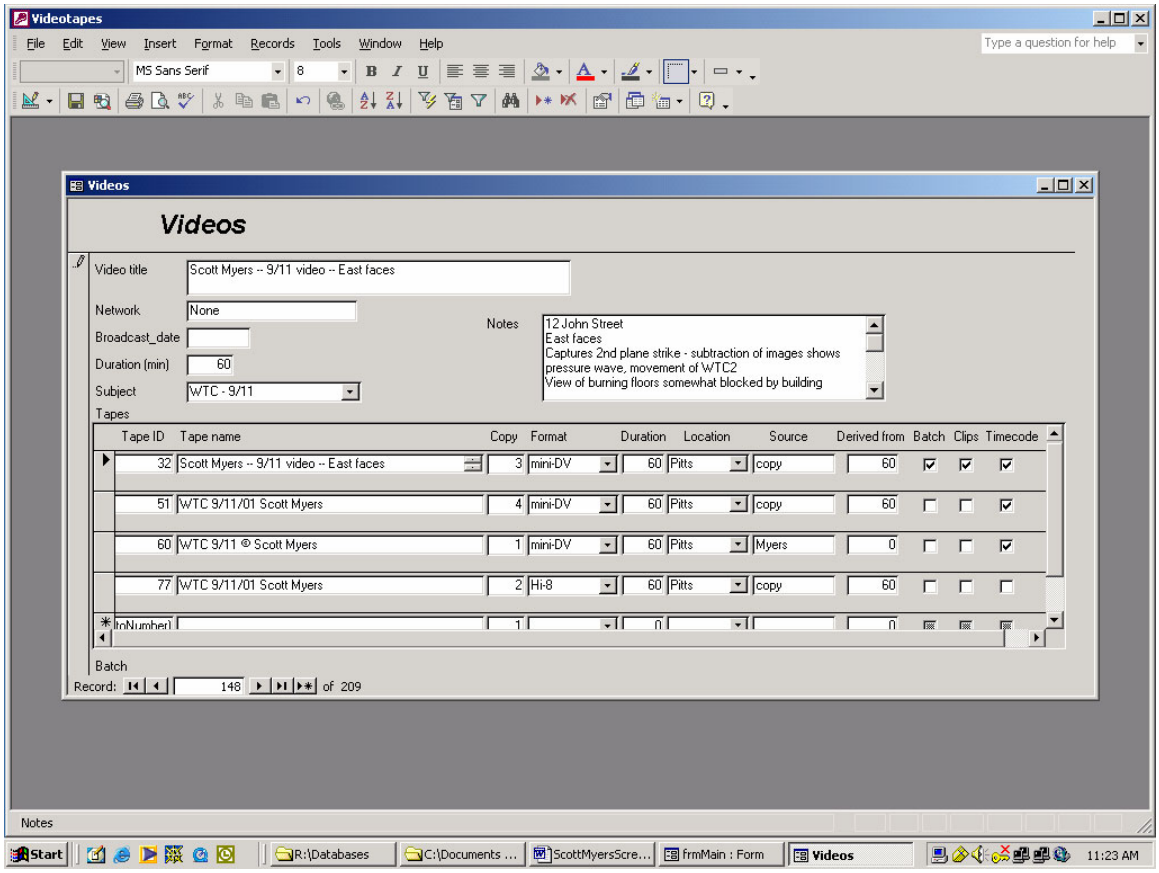


Figure H–1. An example of the VideoList data entry sheet for video assets.

Two separate catalogs, one for photographs and one for video clips, have been created for visual materials collected as part of the Investigation. Each catalog has a similar set of attributes that is used to characterize the assets that are included. These attributes were chosen based on the needs of this task dealing with fire conditions within WTC 1, 2, and 7 and by consultation with members of other project teams. Tables H–1 and Table H–2 list the attributes used for photographic and video catalogs, respectively. A description of each attribute is provided along with details on how information concerning the attribute is input into the worksheet. Figure H–2 shows an example of the first screen for the photographic data entry form.

Cumulus allows thumbnails of entire catalogs or selected subsets to be displayed. This makes it possible to review large numbers of photographs and video clips quickly and to decide which are most likely to be useful for a particular purpose. A variety of asset characteristics can also be shown simultaneously. Typically, the asset name and the time the asset was recorded are displayed. Figure H–3 shows an example of thumbnails taken from the video database.

Table H–1. Attributes for photographic assets.

Attribute	Definition	Entry Choice
Asset Reference	Location of photograph in file system	Set by Cumulus
Categories	List of categories under which the photograph is listed, typically the photographer's name or source	Set by Cumulus
Record Name	File name of photograph	Set by Cumulus
Photographer	Photographer's name	Text
Received from	Where photograph was obtained ("Other" may refer to a third party, for example)	Photographer WWW Other
Original Source	How photograph was added to the collection	Digital Copy of Original Digital Copy from Program Digitized Slide or Negative Digitized Photograph Uploaded from Web
Use Limited	Photographer has requested that use of the photograph be limited	Checkbox
Copyright	A copyright exists	Checkbox
Copyright Agreement	Usage agreement with NIST	Text
Shot From	Location of photographer	Text
Date Recorded	Date and time of shot	Date and time
Time Uncertainty (s)	Number of seconds uncertainty in the time assigned	Integer
View Direction	Location of photographer with respect to the WTC	North Northeast East Southeast South Southwest West Northwest
WTC Faces WTC 1 North Face WTC 1 East Face WTC 1 South Face WTC 1 West Face WTC 2 North Face WTC 2 East Face WTC 2 South Face WTC 2 West Face WTC 7 North Face WTC 7 East Face WTC 7 South Face WTC 7 West Face	Building face(s) visible in the photograph	Checkbox for each choice

Attribute	Definition	Entry Choice
Distance Near Medium Far	Clarity of the photograph Near = Can make out details in windows Medium = Can count windows Far = Unable to count windows	Checkbox for each choice
Building WTC 1 WTC 2 WTC 7 Other Building	Building(s) visible in photograph	Checkbox for each choice
1st Plane Strike	Photograph shows the plane strike on WTC 1	Checkbox
2nd Plane Strike	Photograph shows the plane strike on WTC 2	Checkbox
WTC 1 Collapse	Photograph shows the collapse of WTC 1	Checkbox
WTC 2 Collapse	Photograph shows the collapse of WTC 2	Checkbox
WTC 7 Collapse	Photograph shows the collapse of WTC 7	Checkbox
Street	Street scene, or a street is visible in the photograph	Checkbox
Debris Aircraft Debris Collapse Debris Debris Inside Building Street Debris	Debris is visible in the photograph Type of debris: Aircraft = Can be identified as plane debris (e.g., tires, engines) Collapse = Resulting from collapse Inside Building = Visible through windows or openings Street = On street	Checkbox for each choice
Fireball	Initial fireball from plane strike is visible	Checkbox
Thermal	The thermal is a tall region of the smoke plume that results from the lift caused by the hot gases of the initial fireball	Checkbox
Plume	Smoke plume generated by the fires within the towers and blown downwind. This marker is checked if the smoke plume in the photograph extends farther than a single tower width.	Checkbox
Flames Visible	Flames are visible in the photograph	Checkbox
People Inside Falling Outside	The photograph includes people Inside = People inside the buildings, at the windows or climbing down Outside = People on the street	Checkbox for each choice
Falling building component	The photograph shows a building component falling (e.g., aluminum cladding)	Checkbox
Streamers Falling	The photograph shows a streamer, an object that emits smoke as it falls and leaves a trail	Checkbox
Dripping	Molten material dripping from WTC 2 is visible	Checkbox
Hanging Floor	A sagging or hanging object suggesting a floor is visible within the windows	Checkbox

Attribute	Definition	Entry Choice
Building Core	Photograph shows the core of WTC 1 or WTC 2 — both remained standing briefly during collapse before falling	Checkbox
FDNY FDNY Apparatus FDNY Personnel	FDNY personnel or vehicles are visible, including EMTs, fire trucks, and ambulances	Checkbox for each choice
NYPD NYPD Apparatus NYPD Personnel	NYPD personnel or vehicles are visible, also includes FBI and other police officials	Checkbox for each choice
Impact Aircraft	Photograph shows aircraft approaching WTC 1 or WTC 2 before or during the strike	Checkbox
Other Aircraft	Aircraft other than the impact aircraft are included in the photograph, such as helicopters or fighter jets	Checkbox
Good for Analysis	Mark photograph for possible window-by-window analysis	Checkbox
Analyzed	The photograph has been used for window-by-window analysis	Checkbox
Notes	Notes, including a description of how the photograph was timed	Checkbox

Not all collected visual material is incorporated into the two catalogs. Photographs and videos judged not to contain information directly relevant to the Investigation are not included. Even so, the number of photographs and clips included in the catalogs is huge. At the time of writing, the photographic catalog includes 6,759 assets and the video catalog includes 6,911 assets.

H.3 TIMING OF PHOTOGRAPHS AND VIDEO CLIPS

Since one of the major goals of this task is the development of time lines for fire growth and spread in WTC 1, 2, and 7, it is important to assign times of known accuracy to assets included in the two catalogs. This task is complicated by the absence of accurate times for the majority of visual materials collected.

H.3.1 Digital Timestamps

Modern photographic and video digital cameras often record camera clock times as part of their output. For photographs, this information is usually stored as an integral part of the image in a header known as an Exif file. Similarly, digital video cameras often embed a variety of information, including the camera clock time, as part of what is known as meta data. Software is available for reading these clock times from Exif and other meta data media file formats. While a great help, these times usually still require some adjustment because people do not generally set their camera clocks accurately. In some cases, camera clocks were off by days or even years. Even so, the relative times over the short time period of the events of September 11, 2001, are quite accurate.

Table H–2. Attributes for video assets.

Attribute	Definition	Entry Choice
Asset Reference	Location of video clip in the file system	Set by Cumulus
Categories	List of categories under which the video clip is listed, typically the photographer's name or source	Set by Cumulus
Record Name	File name of video clip	Set by Cumulus
Photographer	Photographer's name	Text
Content	Content of video clip WTC 9/11 Footage = Events before collapse of WTC 7 Street Scene (no timing) Debris field = Ground Zero after WTC 7 collapse Construction = Construction of WTC towers from documentary Normal Operation = Normal operation of building, usually from documentary Animation = Animation of 9/11 events from documentary Still(s) = Photographs contained within documentary Interview = Clip only shows interview	WTC 9/11 Footage Street scene (no timing) Debris field Construction Normal operation Animation Still(s) Interview
Use Limited	Videographer has requested that use of the videotape be limited	Checkbox
Copyright	A copyright exists	Checkbox
Copyright Agreement	Usage agreement arrangements with NIST	Text
Shot From	Location of videographer	Text
Date Recorded	Date and time of beginning of video clip	Date and time
End Recording	Date and time of end of video clip	Date and time
Duration	Number of minutes:seconds contained in clip	Real number
Time Uncertainty (s)	Number of seconds uncertainty in the time recorded / end recording	Integer
View Direction	Location of videographer with respect to the WTC	North Northeast East Southeast South Southwest West Northwest

Attribute	Definition	Entry Choice
WTC Faces WTC 1 North Face WTC 1 East Face WTC 1 South Face WTC 1 West Face WTC 2 North Face WTC 2 East Face WTC 2 South Face WTC 2 West Face WTC 7 North Face WTC 7 East Face WTC 7 South Face WTC 7 West Face	Building face(s) visible in the video clip	Checkbox for each choice
Distance Near Medium Far	Clarity of the video clip Near = Can make out details in windows Medium = Can count windows Far = Unable to count windows	Checkbox for each choice
Building WTC 1 WTC 2 WTC 7 Other Building	Building(s) visible in video clip	Checkbox for each choice
1st Plane Strike	Clip shows the plane strike on WTC 1	Checkbox
2nd Plane Strike	Clip shows the plane strike on WTC 2	Checkbox
WTC 1 Collapse	Clip shows the collapse of WTC 1	Checkbox
WTC 2 Collapse	Clip shows the collapse of WTC 2	Checkbox
WTC 7 Collapse	Clip shows the collapse of WTC 7	Checkbox
Street	Street scene, or a street is visible in the video clip	Checkbox
Debris Aircraft Debris Collapse Debris Debris Inside Building Street Debris	Debris is visible in the video clip Type of debris: Aircraft = Can be identified as plane debris (e.g., tires, engines) Collapse = Resulting from collapse Inside Building = Visible through windows Street = On street	Checkbox for each choice
Fireball	Initial fireball from plane strike is visible	Checkbox
Thermal	The thermal is a tall region of the smoke plume that results from the lift caused by the hot gases of the initial fireball	Checkbox
Plume	Smoke plume generated by the fires within the towers and blown downwind. This marker is checked if the smoke plume in the video clip extends farther than a single tower width.	Checkbox
Flames Visible	Flames are visible in the video clip	Checkbox

Attribute	Definition	Entry Choice
People Inside Falling Outside	The video clip includes people Inside = People inside the buildings, at the windows, or climbing down Outside = People on the street	Checkbox for each choice
Falling building component	The video clip shows a building component falling (e.g., aluminum cladding)	Checkbox
Streamers Falling	The video clip shows a streamer, an object that emits smoke as it falls and leaves a trail	Checkbox
Dripping	Molten material dripping from WTC 2 is visible	Checkbox
Hanging Floor	A sagging object suggesting a floor is visible within the windows	Checkbox
Building Core	Video clip shows the core of WTC 1 or WTC 2 – both remained standing briefly during collapse before falling	Checkbox
FDNY FDNY Apparatus FDNY Personnel	FDNY personnel or vehicles are visible, including EMTs, fire trucks, and ambulances	Checkbox for each choice
NYPD NYPD Apparatus NYPD Personnel	NYPD personnel or vehicles are visible, also includes FBI and other police officials	Checkbox for each choice
Aircraft Impact Aircraft Other Aircraft	Aircraft are visible in the video clip Impact: Shows aircraft approaching WTC 1 or WTC 2 before or during the strike Other: Helicopters or fighter jets	Checkbox for each choice
Major Change Major Fire Change Major Smoke Change Windows Opened	One of the following events takes place in the video clip: Major Fire Change: Fire flares up, dies down, or spreads to a new region Major Smoke Change: Smoke bursts, dies down, or spreads to a new region Windows Opened: Window breaks open, either due to fire or to people	Checkbox for each choice
Good for Analysis	Mark video clip for possible window-by-window analysis	Checkbox
Analyzed	The video clip has been used for window-by-window analysis	Checkbox
Notes	Notes, including a description of how the video clip was timed	Text

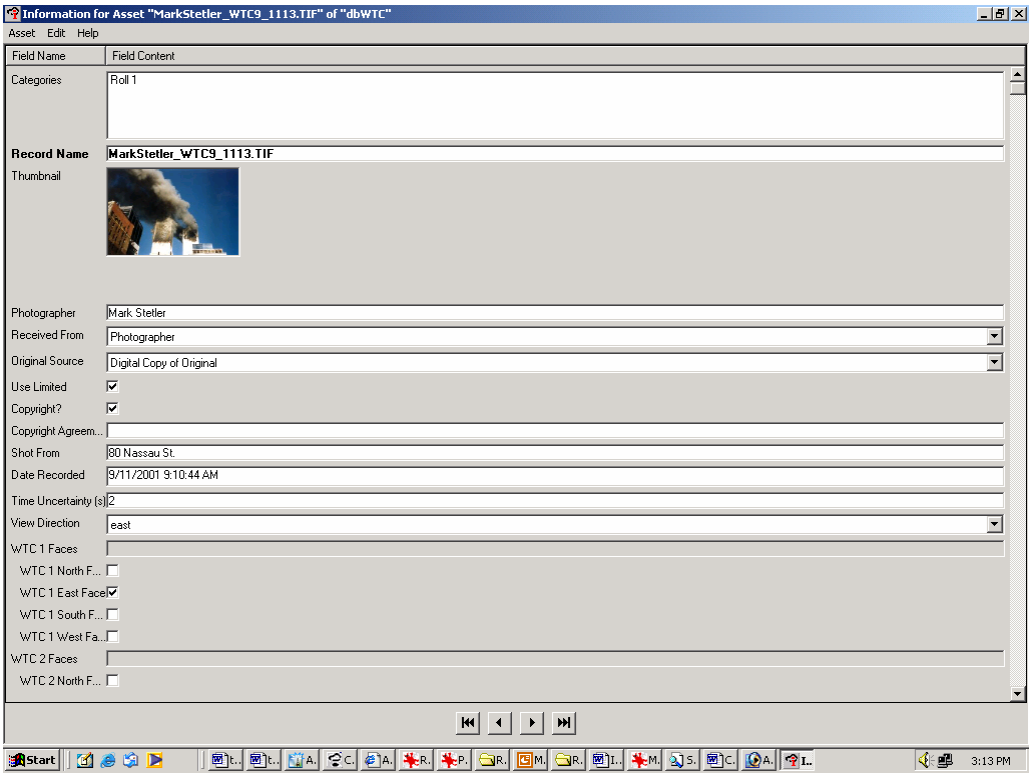


Figure H–2. An example of the first page of the Cumulus data entry sheet for photographic assets. Thumbnail © 2001 Mark Stetler.

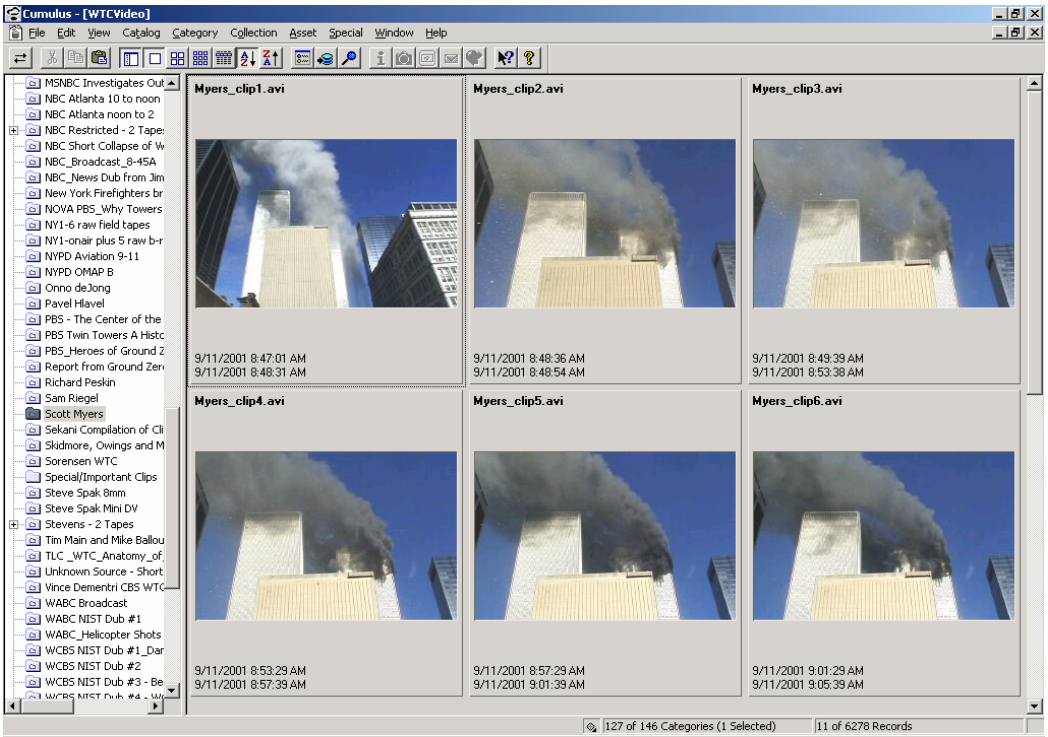


Figure H–3. An example of a Cumulus asset screen display for the video database. Thumbnails are shown along with the time and dates when the recording started and ended. Thumbnails © 2001 Scott Meyers.

Occasionally analog photo and video cameras imprint a time stamp on their outputs that can provide relative times similar to Exif or meta data, but generally there is no time information available, and such material must be timed in some other way. Some of the approaches used are described later in this section.

Photograph Tools

In order to make the best use of the information embedded in digital photographs, software was required to retrieve the Exif file information and software to adjust the recorded clock times. The commercial software package CatDV is able to retrieve meta data embedded in a variety of media formats, including digital photographs and mini-DVs. The Access database PhotoTiming was written for the purpose of determining the actual times for a set of photographs given the Exif time for each and an accurate time reference. For a set of photographs sharing a common clock from the same digital camera, an accurate time for a single photograph is sufficient to set the times for the entire set. Figure H–4 shows a PhotoTiming data sheet for a selected photographer. A file generated by CatDV containing the Exif data for each photograph, if available, is read into PhotoTiming. The equivalent Exif and actual times are entered into the appropriate fields at the upper right of the data sheet. Selection of the Calculate Photo Times button fills the Actual Time column with the appropriate value for each Exif time. In this example, the Exif time was found to be off by 62 s.

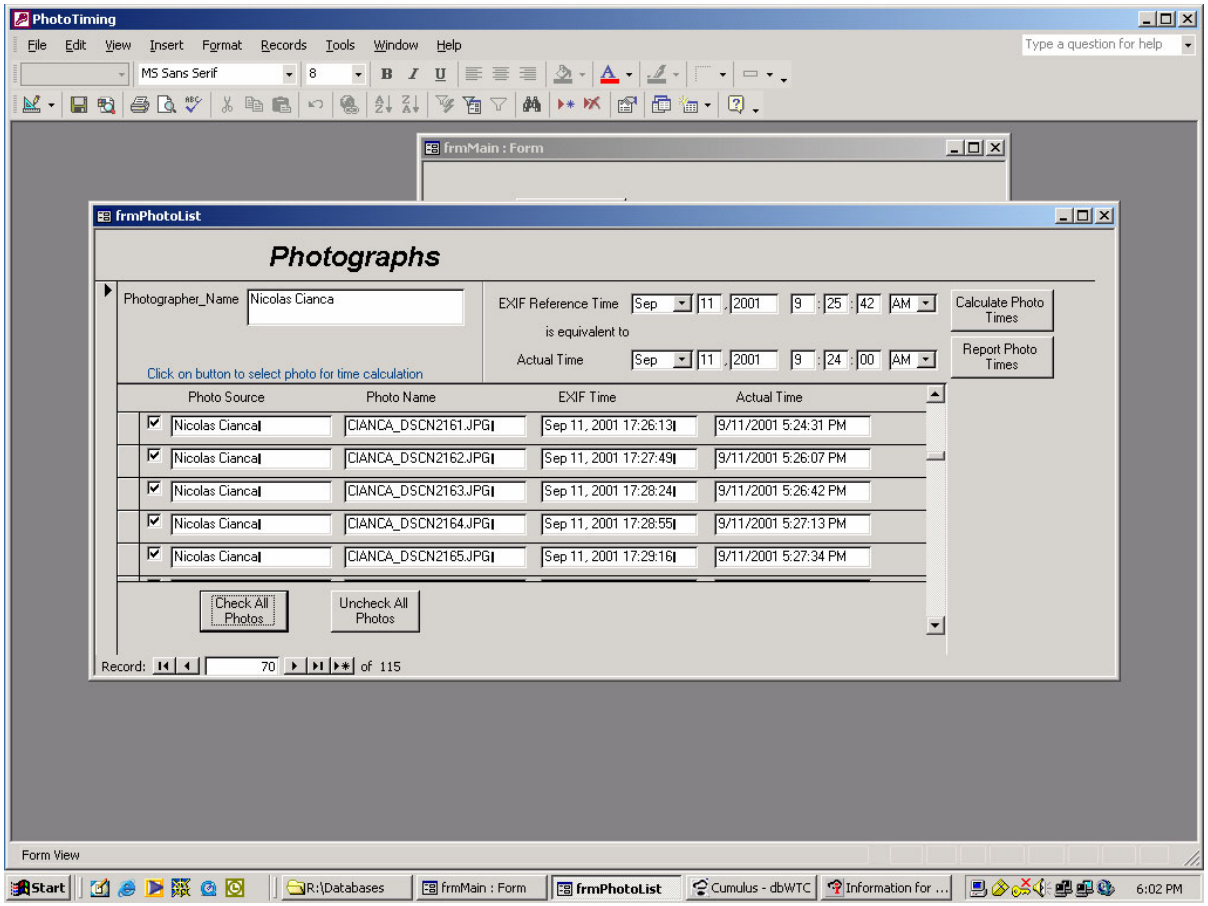


Figure H–4. An example of the PhotoTiming sheet for calculating times for photographs containing Exif meta data.

Video Tools

In addition to containing the video database described in Section H.2.3, VideoList also assists with timing the clips from a videotape. This function is similar to that in the PhotoTiming tool. For a broadcast video that was filmed in real time, the timing of every clip in the video, except for replays, can be set from knowing the time at a single point. An example is shown in Figure H–5. A clip file generated in Adobe Premiere for a specified video is read into VideoList. The mini-DV time of an event in the video whose timing is known, such as the moment of the second plane strike, is identified. Both times are entered into the fields at the upper right of the data sheet. Clips to be timed (excluding replays) are identified by a check mark, and the requested calculation results in the actual times in and out for each clip as shown in Figure H–5. This tool is also useful in calculating timings for continuous video segments broken into multiple clips.

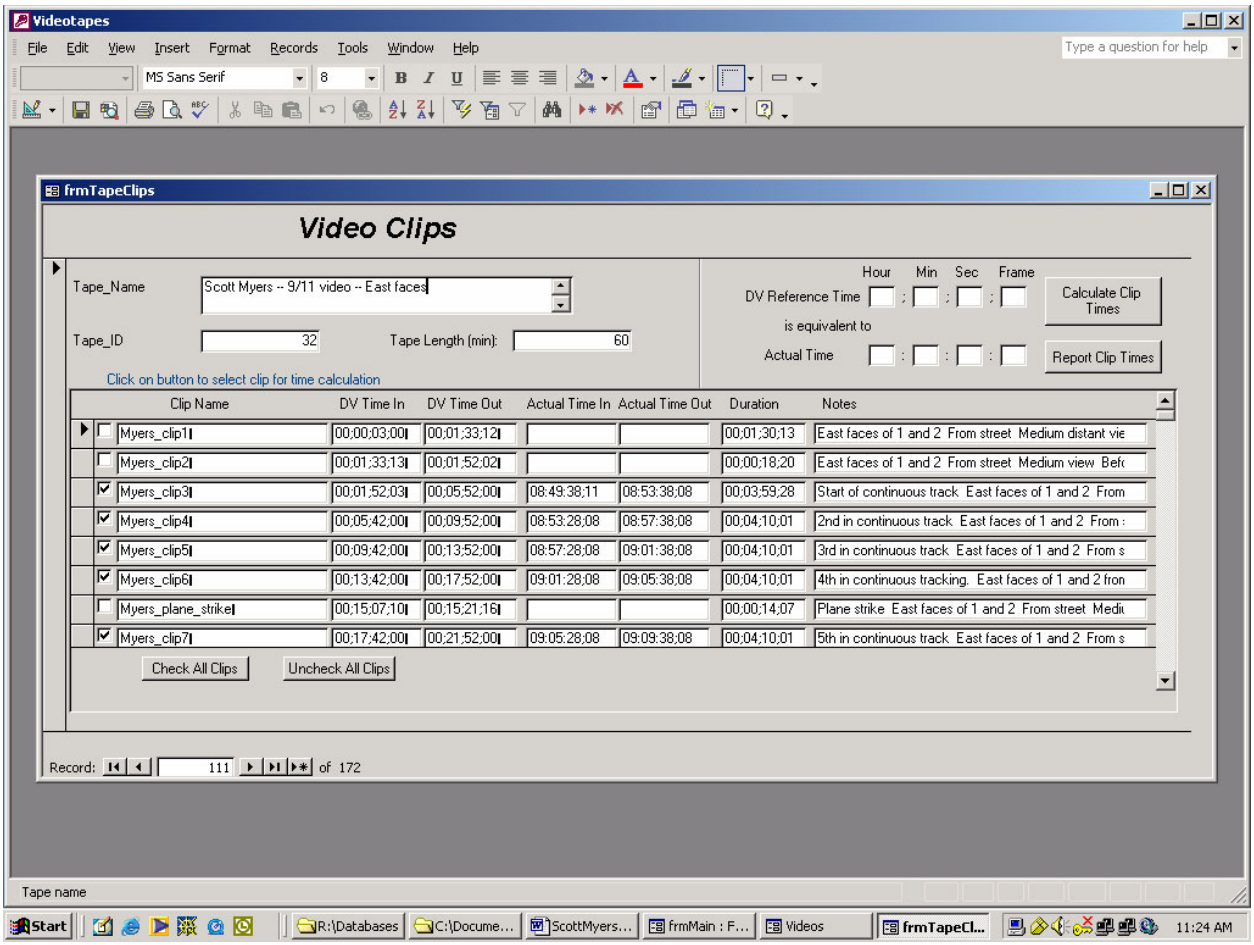


Figure H–5. An example of the VideoList sheet for calculating clip times for video assets.

For each mini-DV video that contains meta data, CatDV is used to extract the clock times for the In and Out point for each clip. These values enable the timing of every clip in the video from a single reference time.

H.3.2 Reference Time

Faced with the timing considerations above, a timing scheme was developed in which all of the times in the databases are placed on a relative time scale tied to a single well-defined event. Due to the large number of different views available, the moment the second plane struck WTC 2 was chosen to be this time. This event was defined to have occurred at 9:02:54 a.m. based on times for major events included in the earlier Federal Emergency Management Agency (FEMA) report (McAllister 2002) describing the events of September 11, 2001.

H.3.3 Timing Techniques

Once the reference time was chosen, it was possible to place times on videos that showed the second plane strike. By matching other photographs and videos to these initially assigned videos, the assignments were extended to visual materials that did not include the primary event. By such a bootstrap process, it was possible to place photographs and videos extending over the entire period of the event on a single time line. Sets of photographs containing Exif times and video clips that either contained meta data or were continuous over relatively long periods were particularly useful for this purpose because a single time assignment would allow the entire series to be timed. Sets of photographs recorded on film or analog videos that were frequently turned on and off caused the most difficulty in timing, and individual matches were required for each photo or video clip.

Matching visual images and assigning times has turned out to be a demanding task requiring unique approaches. A variety of characteristics have been employed to match times in different photographs and videos. These include distinct shadows cast on the buildings by the smoke plumes, the appearance and locations of smoke and fire plumes, the occurrence of well-defined events such as a falling object or the sudden appearance of smoke, and a variety of other unlikely clues such as a clock being recorded in an image.

To assist in the timing process, relative times for the five major events of September 11, 2001: first plane strike, second plane strike, collapse of WTC 2, collapse of WTC 1, and collapse of WTC 7 have been determined with 1 second accuracy. These times are summarized in Table H–3. Note that the building collapse times are defined to be when the entire building is first observed to start to collapse. In the case of WTC 7, a penthouse on the roof sank into the building before the main collapse started.

Table H–3. Times for major events of September 11, 2001.

Event	Relative Time from Visual Analysis	Adjusted Time from Television Broadcasts	Time Reported in the FEMA Study
First plane strike	8:46:25 a.m.	8:46:30 a.m.	8:46:26 a.m.
Second plane strike	9:02:54 a.m.	9:02:59 a.m.	9:02:54 a.m.
Collapse of WTC 2	9:58:54 a.m.	9:58:59 a.m.	9:59:04 a.m.
Collapse of WTC 1	10:28:20 a.m.	10:28:25 a.m.	10:28:31 a.m.
Collapse of WTC 7	5:20:47 p.m.	5:20:52 p.m.	5:20:33 p.m.

It is not only important to assign relative times for photographs and videos, but also to estimate how accurately they are known. For this reason, timing uncertainties are estimated for each determination and are included in the databases.

The bootstrap timing process was initially quite difficult. However, team members' timing skills improved with practice at the same time as more visual material became available and the number of timed assets increased. At the present time, 3,032 of the 6,759 catalogued photographs and 2,673 of the 6,911 video clips in the databases are timed with assigned relative accuracies of 3 seconds or better.

H.3.4 Absolute Time Accuracy

Many of the news broadcasts on September 11, 2001, included small clocks, known in the industry as "bugs," imprinted on the screen. As such broadcasts were timed, it became apparent that there were small differences between times for the second plane strike based on these bugs and the time used as the basis for the database. Checks with several broadcasters indicated that the bugs should be quite close to the actual time because their clocks are regularly updated from highly accurate sources such as geopositioning satellites or the precise atomic-clock-based timing signals provided by NIST as a public service. Careful checks showed small time differences between different video recordings, but these were generally less than 1 second. These small discrepancies are likely due to variations in transmission times resulting from the different pathways that the video signals take to the sites where they are recorded. Based on four such video recordings, the time of the second plane impact is estimated as 9:02:59 a.m., or 5 seconds later than the time assumed in developing the database. The estimated uncertainty is 1 second. Table H–3 compares times for the major events taken from the database, adjusted to television time, and reported in the FEMA report (McAllister 2002). Possible explanations for the observed differences are still under investigation. Because times based on the television broadcasts appear to be accurate (i.e., those in column 3 of Table H–3), 5 seconds will be added to times included in the databases when precise times are reported for the Investigation.

H.4 ANALYSIS OF VISUAL IMAGES

Once the two visual databases became available, it was possible to use the images to begin characterizing the events of September 11, 2001. Some of the images are quite close up and can be used to learn specific details concerning the towers. As an example, Fig. H–6 shows an image of the east face of WTC 2 recorded at 9:26:20 a.m., and Fig. H–7 shows an enlarged portion of the same photograph. The photograph has been enhanced using Adobe Photoshop, and lettering has been added to indicate the floors and the numbering system used to identify specific windows in the tower. The amount of detail available is evident. For instance, large piles of debris are present on the north side of the tower on floors 80 and 81, and locations with fires visible or with windows missing are easily identified.

H.4.1 Window Numbering

The system used to describe window locations in the two towers and WTC 7 requires some elaboration. It is based on the outer-wall column numbering system used in plans for the buildings. First, consider the towers. In these structures individual windows were placed between two exterior columns. In order to refer to a particular window the designation for the column to the right as viewed from the outside is assigned to that window. These columns are numbered from 1 to 59 from right to left across a tower face, and windows are numbered from 1 to 58. Faces for the towers are also assigned numbers as follows; WTC 1—north: 1, east: 2, south: 3, and west: 4, and WTC 2—west: 1, north: 2, east: 3, and south: 4. By combining the floor number, the face number and a column number, a specific window on one of the

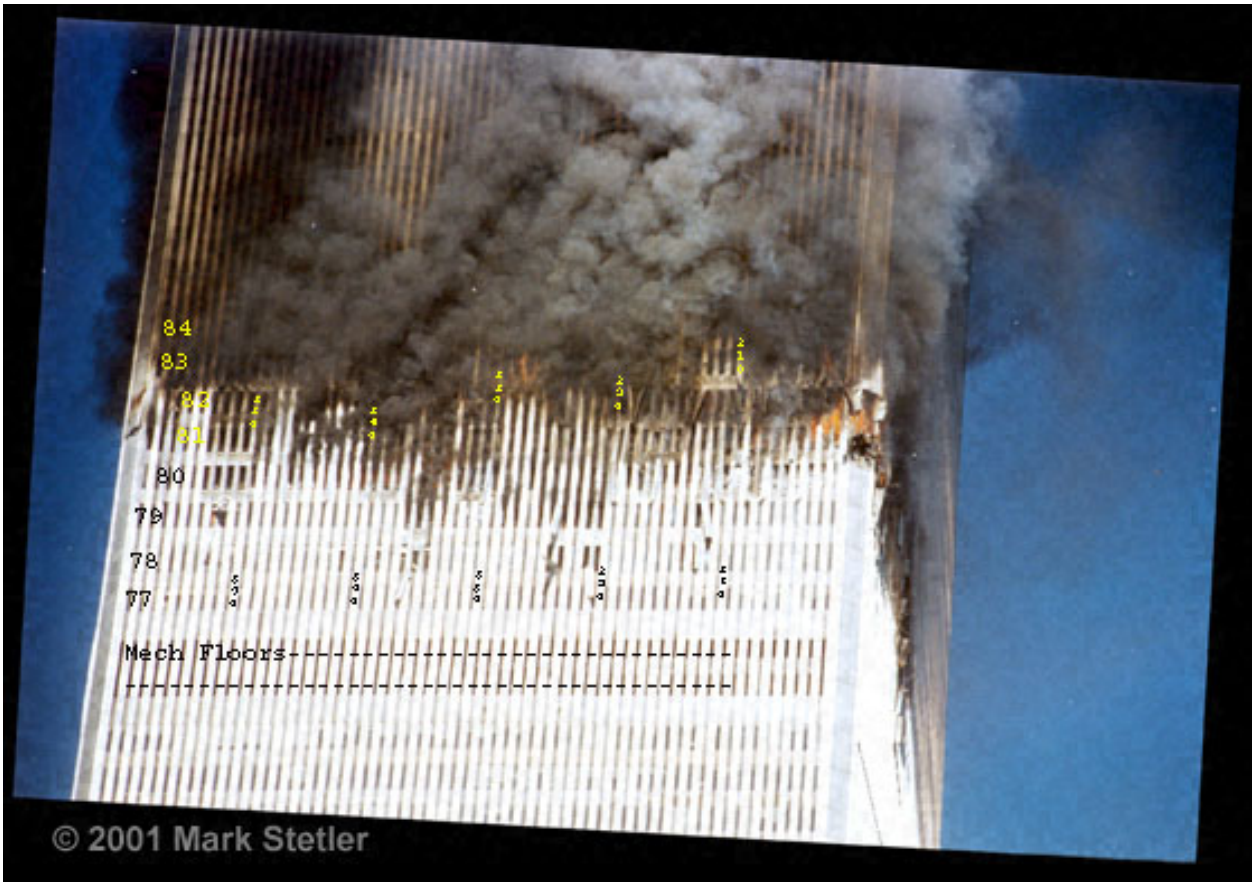


Figure H–6. Photograph taken at 9:26:20 a.m. on September 11, 2001, showing the east face of WTC 2. It has been enhanced, and lettering indicating floors and columns has been added.

towers can be identified. As an example, for WTC 1, the number 94-214 refers to the fourteenth window from the right on the east face of floor 94.

The window numbering system is somewhat different for WTC 7. It is also based on the outside column numbers, but in this building the numbering of columns was continuous around the structure and ranged from 1 to 57. Column 1 was located at the northwest corner of the building, and the numbering proceeded counter clockwise around the building faces with columns 15, 28, and 42 located at the southwest, southeast, and northeast corners, respectively. Note that the total number of perimeter columns is actually 58. An extra column, numbered 14A, was included on the west face between columns 14 and 15. Unlike the towers, the number of windows to the right of a given column varied from one to five depending on location. In some cases, the windows are located in front of the column. Individual windows to the right of a column are assigned letters increasing from left to right as seen from the outside. As an example, 12-45c refers to a window on the north face of WTC 7 that is the third window to the right of column 45 on floor 12.

Figure H–7. This photograph is cropped from the image shown in Figure H–6. It was taken on September 11 and shows the east face of WTC 2 at the northeast corner from floor 77 to floor 82. Note the large piles of debris evident on floor 80 and floor 81.

H.4.2 Fire Properties

Photographs and video images have been used to characterize a number of properties relevant to fire growth and spread in the towers as a function of time. Specific properties addressed include whether or not fire and smoke are present and whether windows are still in place. When smoke and/or fire are present, additional details concerning their appearances are documented. A numbered coding system is used to describe these characteristics. The key for this numbering system is shown in Fig. H–8.

H.4.3 Window-by-Window Assessment

The key in Fig. H–8 is used as the basis for a window-by-window assessment of the towers. The results are coded in three separate data sheets using Microsoft Excel. The floor and window locations are identified using the numbering system described in the last section. Separate files containing the three data sheets are generated for each face of a tower and time analyzed. Figure H–9 shows a portion of such a data sheet describing fires (i.e., sheet one) on the east face of WTC 1 around 9:42 a.m.

KEY FOR ANALYSIS

Sheet #1: Fire Visible

0	No fire
1	Spot fire
2	Fire visible inside
3	External flaming
9	Not visible

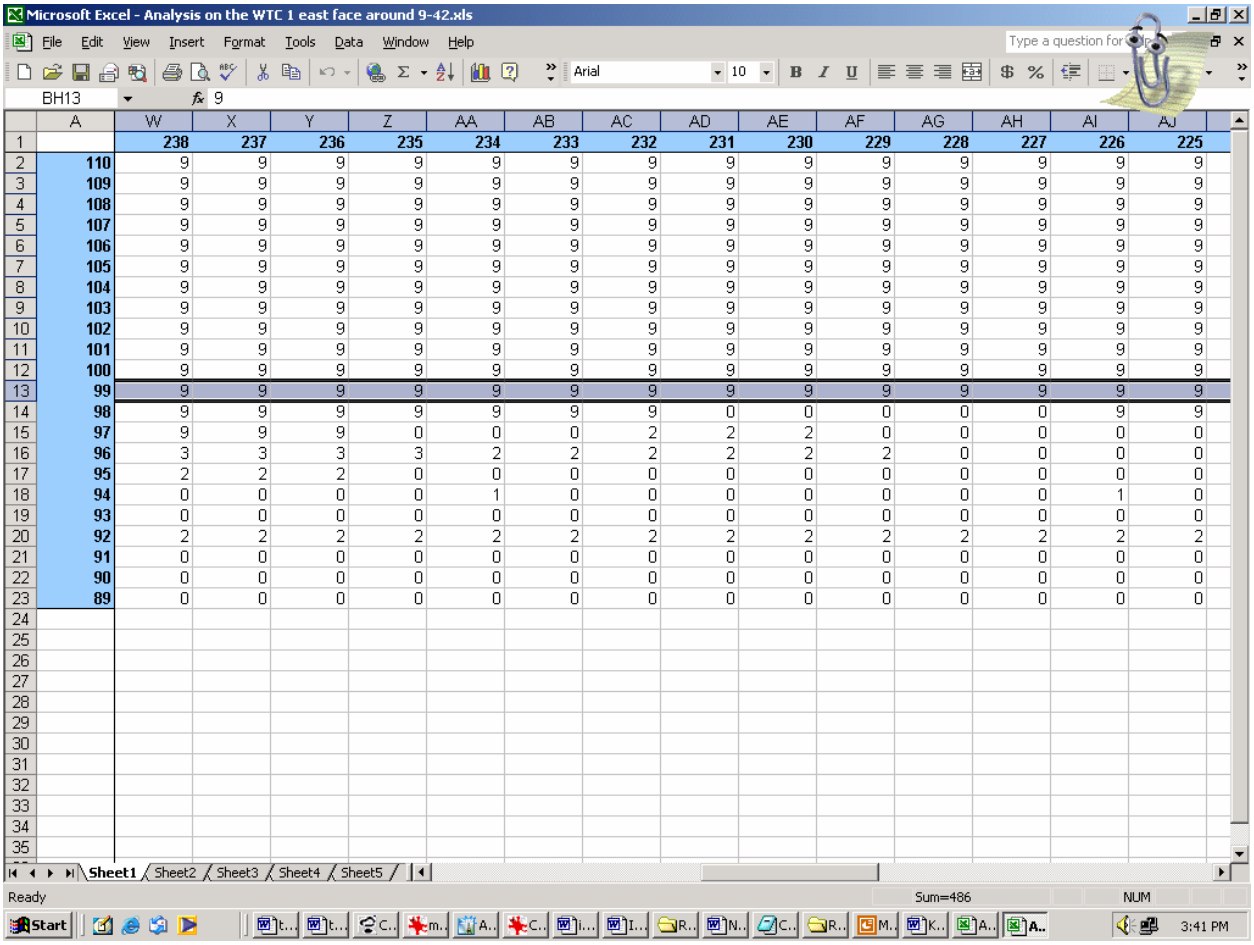
Sheet #2: Smoke

0	No smoke evident
1	"Light smoke"
2	"Heavy smoke"
9	Not visible

Sheet #3: Windows

0	Window open
1	Window in place
9	Not visible

Figure H–8. The key used to describe observations with regard to fire, smoke, and window breakage in Excel data files for individual windows in the two towers.



	A	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
1		238	237	236	235	234	233	232	231	230	229	228	227	226	225
2	110	9	9	9	9	9	9	9	9	9	9	9	9	9	9
3	109	9	9	9	9	9	9	9	9	9	9	9	9	9	9
4	108	9	9	9	9	9	9	9	9	9	9	9	9	9	9
5	107	9	9	9	9	9	9	9	9	9	9	9	9	9	9
6	106	9	9	9	9	9	9	9	9	9	9	9	9	9	9
7	105	9	9	9	9	9	9	9	9	9	9	9	9	9	9
8	104	9	9	9	9	9	9	9	9	9	9	9	9	9	9
9	103	9	9	9	9	9	9	9	9	9	9	9	9	9	9
10	102	9	9	9	9	9	9	9	9	9	9	9	9	9	9
11	101	9	9	9	9	9	9	9	9	9	9	9	9	9	9
12	100	9	9	9	9	9	9	9	9	9	9	9	9	9	9
13	99	9	9	9	9	9	9	9	9	9	9	9	9	9	9
14	98	9	9	9	9	9	9	9	0	0	0	0	0	9	9
15	97	9	9	9	0	0	0	2	2	2	0	0	0	0	0
16	96	3	3	3	3	2	2	2	2	2	2	0	0	0	0
17	95	2	2	2	0	0	0	0	0	0	0	0	0	0	0
18	94	0	0	0	0	1	0	0	0	0	0	0	0	1	0
19	93	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	92	2	2	2	2	2	2	2	2	2	2	2	2	2	2
21	91	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	89	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure H–9. A portion of the Excel spreadsheet describing fires on the east face of WTC 1 around 9:42 a.m. is shown. The numbers at the left refer to floors, and those at the top are the window numbers.

While the data sheets capture the desired behaviors, it is very difficult to use them to track changes without visualizing the results in some way. Two approaches have been developed for this purpose. The first employs a Web-based system that generates color-coded maps of the results contained in the data sheets. Figure H–10 shows such a map for the fire data included in the data sheet shown in Fig. H–9. The second approach uses the program Smokeview (Forney and McGrattan 2003; Forney, Madrzykowski, and McGrattan 2003) to generate a time-dependent visualization of the results. Smokeview was developed at NIST in order to display the results of fire dynamics calculations. In the current application, it is used to visualize the properties of interest on a three-dimensional representation of a tower façade as a function of time. Because Smokeview allows the point of view to be varied at will, this approach is a powerful means for investigating the temporal behavior of the fires on different faces of the tower. Figure H–11 shows a frame taken from a visualization in which results from the fire and windows data sheets for WTC 2 have been combined.

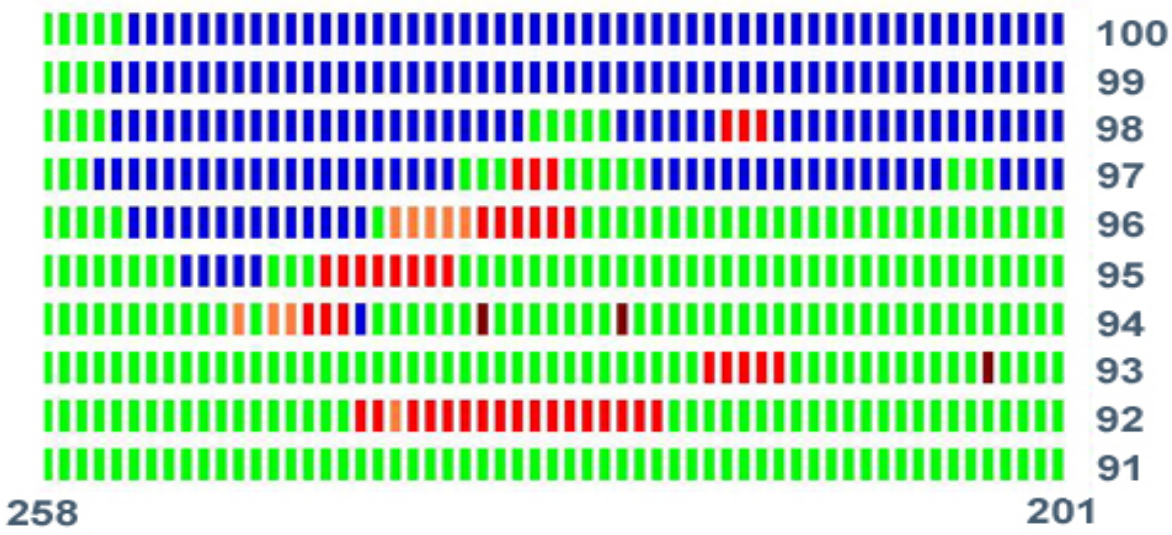


Figure H–10. A representation of fires for floors 91 to 100 on the east face of WTC 1 around 9:42 a.m. is shown. Results are taken from the Excel spreadsheet shown in Figure H–13. The color coding is based on the key shown. The color assignments are: 0-No fire, 1-Spot fire, 2-Fire visible inside, 3-External Flaming, and 9-Can't see.

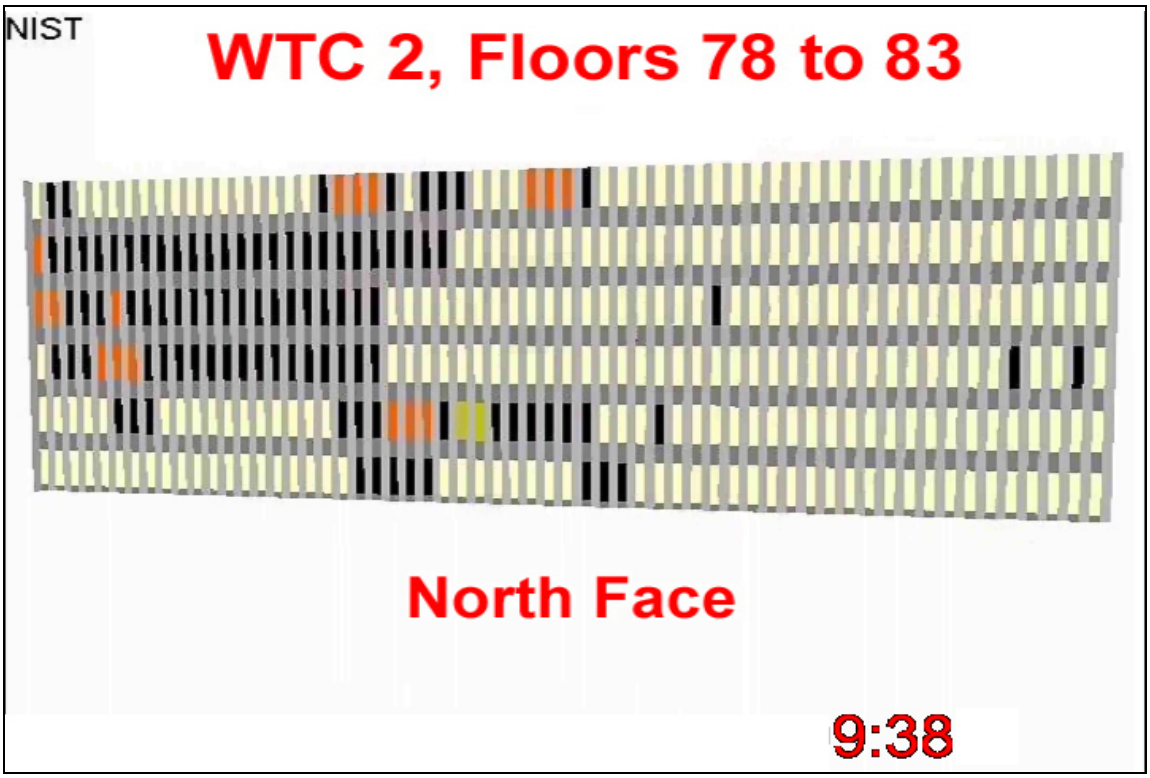


Figure H–11. A single frame from a time-dependent visualization generated by Smokeview is reproduced here. The frame is a three-dimensional representation of the condition of windows and fires on WTC 2 from the time the second tower was struck at 9:02:59 a.m. until it collapsed at 9:58:59 a.m. The color assignments are: – window in place, – missing window, – external flaming, – fire inside, and – spot fire.

H.5 INITIAL DAMAGE PATTERNS ON WTC 1 AND WTC 2 DUE TO THE PLANE STRIKES

Close-up photographs and videos have been used to characterize the initial damage to the façades of the towers struck by the two planes along with precise determinations of the locations of the plane strikes. For WTC 2, analysis of videos has also been employed to estimate the speed of the airplane that struck the tower and to show that the tower swung back and forth for several minutes after it was struck. The period of the swinging has also been determined.

H.5.1 WTC 1

Damage Resulting from Plane Strike

A detailed drawing of the damage to the steel façade of WTC 1 was included in the FEMA *World Trade Center Building Performance Study* (McAllister 2002). A careful inspection using photographs and videos in the database confirmed the accuracy of this analysis. Figure H–12 shows a drawing that represents this damage. It is similar to that included in the FEMA report, but it incorporates several minor changes that better reflect the geometry of the north face of WTC 1 in the vicinity of the plane strike.

It was observed that the wing tips and the end of the vertical stabilizer at the plane's tail section damaged the aluminum column covers on the steel façade without cutting through the steel below or completely removing the covers. By inspection it was possible to map out locations on columns where the wingtips and the vertical stabilizer struck the tower. These locations were then transferred to the representation of the damaged steel façade shown in Fig. H–12 and are represented by dashed lines, with wings to the right and left and the vertical stabilizer in the center. The good agreement between the damage pattern and the wing tip locations is evident. It is reported in the FEMA report (McAllister 2002) and widely in the media that American Airlines Flight 11 struck floors 94 to 98 of WTC 1. The dotted horizontal lines on the left side of Fig. H–12 indicate the locations of concrete floors. It can be seen that while the tip of the left wing of the aircraft struck very close to the base of floor 94, the wing end marked column 153 at the very top of floor 93. It is evident from the figure that the right wing actually struck well up on floor 99 on column 109. The impacted floors therefore range from floor 93 to floor 99.

Fireballs and Missing Windows

Additional insights into the initial damage inflicted on the towers by the plane strikes can be obtained by considering locations where fireballs are observed immediately following the plane strikes as well as locations where windows are missing. Videos and photographs recorded during and immediately following the plane strike on WTC 1 show that significant fireballs formed at the plane strike location on the north face, as well as near the center of the east face and on the western side of the south face. Figure H–13 compares window damage for the four sides of WTC 1 immediately after the plane strike. The floors shown extend from 91 to 100. The missing windows on the north face are consistent with the plane strike location and strike angle. The plane struck very close to the center of the face. Interestingly, the damage on the east and west faces appears to be asymmetric with a much higher number of windows missing on the east face than on the west. This observation is consistent with the formation of a fireball on the east side of the tower and not on the west side. Areas obscured by smoke are also much larger on

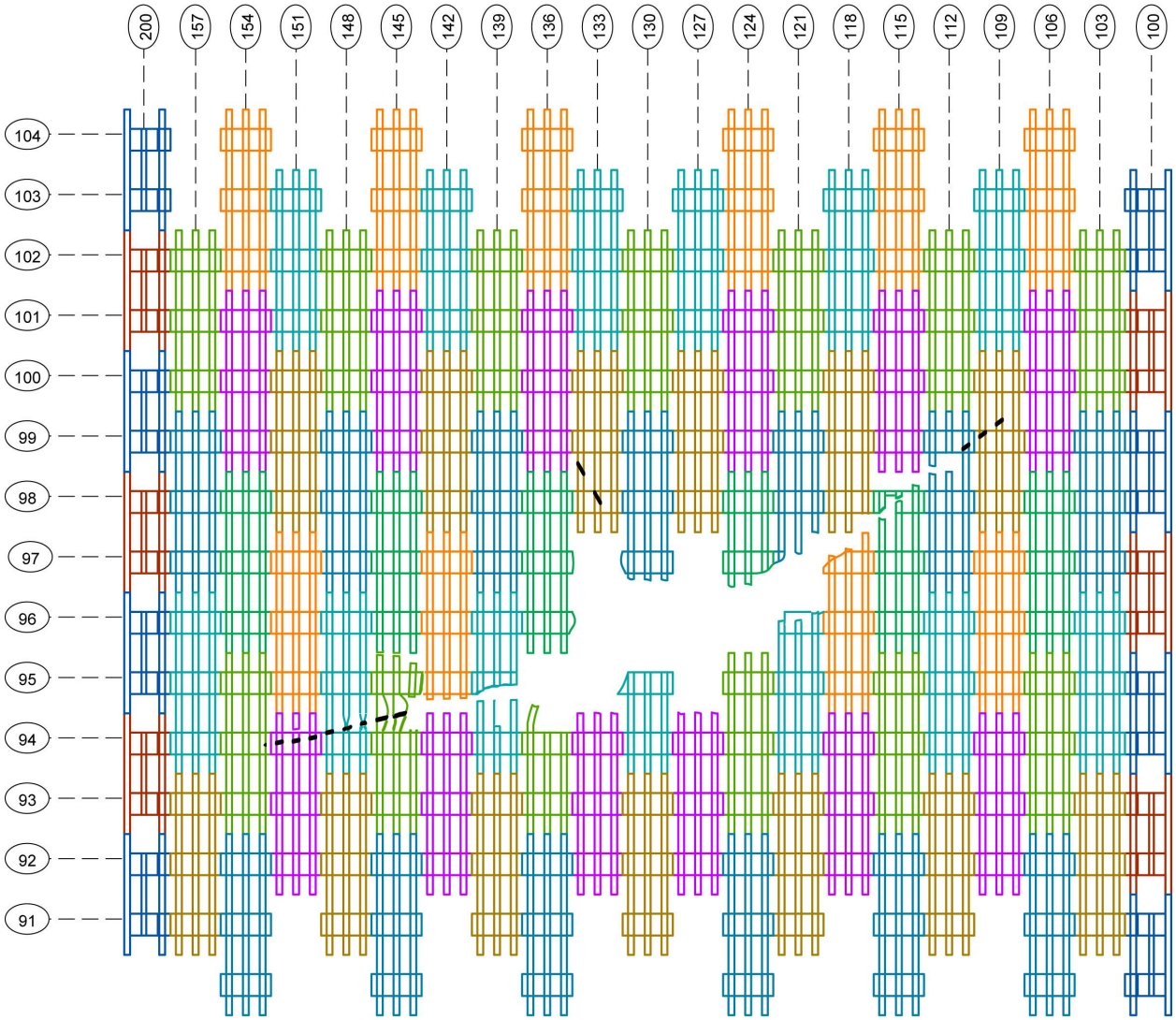


Figure H–12. A drawing of the damage to the steel façade of WTC 1. The dark dotted lines show locations where the airplane wings and vertical stabilizer marked the aluminum cladding on columns.

the east side suggesting that more fire is present on this face as well. An asymmetry is also apparent on the south face where only a single window is missing on the east side while numerous windows are missing and significant smoke is present on the west side. Taken together, these observations suggest that debris and fuel from the airplane as well as any building materials and contents tended to pass straight across the building on the west side, while material on the east side was somehow reflected and more heavily damaged the east face.

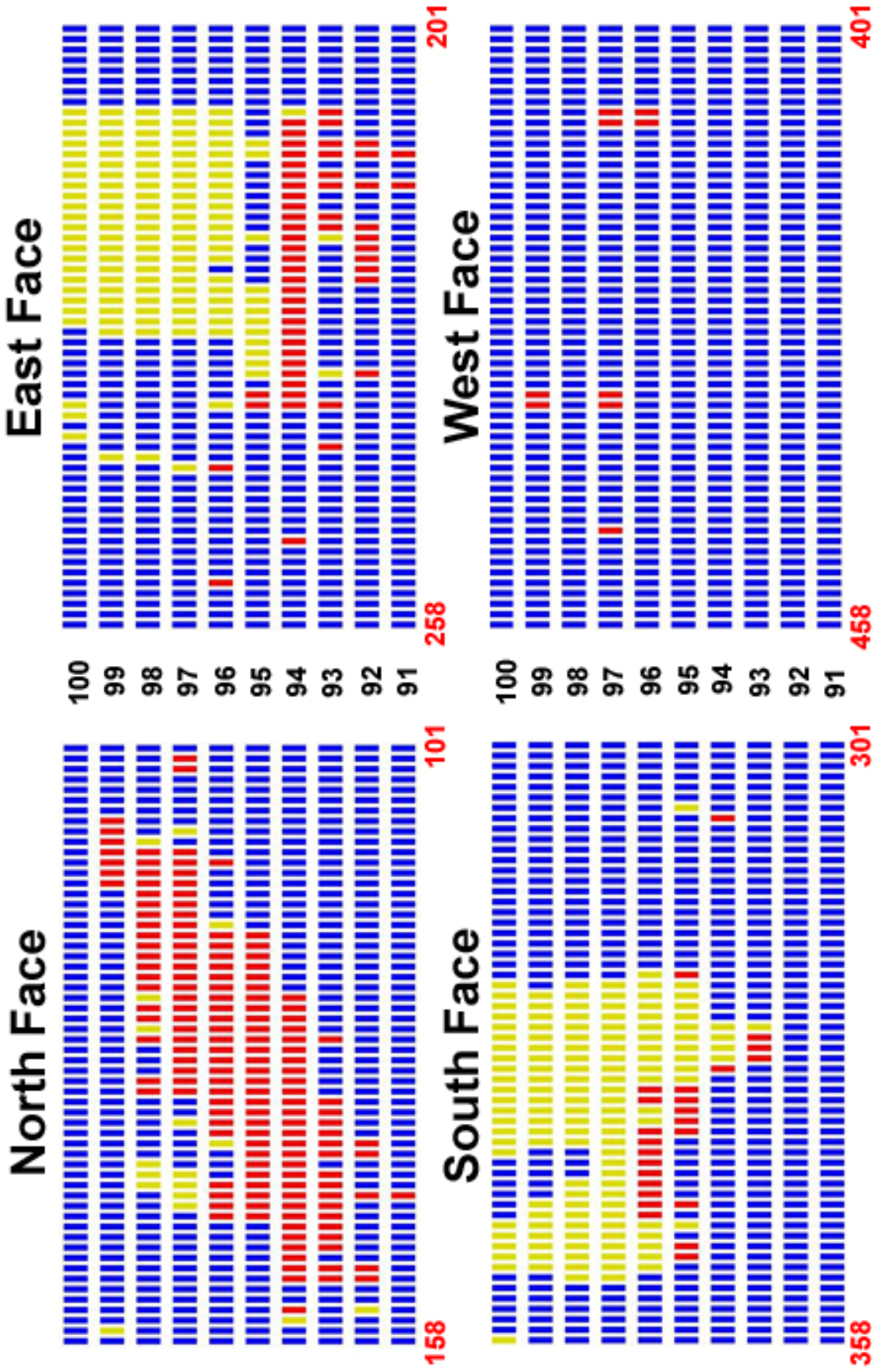


Figure H–13. The condition of windows is shown for the four faces of WTC 1 around 8:47 a.m. shortly after it was struck by American Airlines Flight 11. The colors represent - window open, - window in place, and - not visible.

Panel Section in Street

A photograph supplied by the NYPD provided additional details with regard to the initial damage suffered by WTC 1. Figure H–14 shows a full three-story three-column-wide steel panel section lying on the corner of Cedar Street near its intersection with West Street. This location is to the south of and roughly 210 m from the south face of WTC 1. The photograph was taken prior to the collapse of either tower. Closer inspection shows that there is an aircraft wheel embedded in one of the windows. The most likely source location for this panel section has been identified as being near the center of the south face of WTC 1 (i.e., columns 329 to 331) and extending from the middle of floor 93 to the middle of floor 96. This conclusion remains tentative since, as indicated in Fig. H–13, the area is obscured by smoke in all of the close-up photographs of the area in NIST's possession. If the location is identified correctly, the wheel is stuck in window 95-329.

H.5.2 WTC 2

Calculation of Plane Speed

One of the videographers who provided material to the Investigation filmed from the top of his apartment building located to the east of the WTC complex. His camera was located on a tripod so that the images are very steady. One of the events he captured was United Airlines Flight 175 as it approached WTC 2. Figure H–15 is a series of cropped frames captured from this video that show the plane approaching the building.

The images included in Fig. H–15 have been used to determine the speed of the plane as it approached the tower. This is done by identifying the locations of the nose and tail of the airplane relative to a fixed point defined to be the point on the frame where the plane passes out of sight behind the corner of the building. The plane is very nearly level relative to this point, so it is appropriate to simply count the number of picture elements, pixels, between this location and the two measurement points on the aircraft.

This analysis, which presumes that the aircraft at this time travels in a straight path such that the nose and tail pass through the same point in space, has the advantage of being independent of the orientation of the flight path with respect to the line of sight of the observer.

Figure H–16 shows the locations of the two points as a function of time. Using linear least squares curve fits, the exact relative times when the nose and tail pass the reference location are estimated. The difference between these two times is the period required for the entire length of the aircraft to pass the reference location. The result is 0.1939 s. Since the length of the plane is known to be 155.0 ft, the speed can be determined simply by dividing this length by the passage time to give 155.0 ft/0.1939 s = 799 ft/s = 545 mph. An uncertainty estimate based solely on the uncertainty in the determined time difference yields a value of ±18 mph with 95 percent confidence.

Figure H–14. Photograph showing a full panel section lying in Cedar Street near its intersection with West Street. An aircraft wheel can be seen imbedded in one of the windows. The building behind the panel is Saint Nicholas Greek Orthodox Church and the lower section of WTC 2 can be seen across Liberty Street.

Note that the airplane speed and uncertainties are slightly different than listed in an earlier report (NIST 2003) due to a correction of the plane length to reflect the actual distance between the nose and the end of the body at the rear stabilizer and a math error in the uncertainty calculator. Uncertainties associated with aircraft motion that are not aligned with the aircraft body are judged to be less than the uncertainties in plane passage time.

Observation of WTC 2 Sway Following the Plane Strike

Close examination of the video revealed a perceptible movement of WTC 2 after it was struck by the aircraft. The building rocked back and forth much as a pendulum for at least 4 minutes. Image

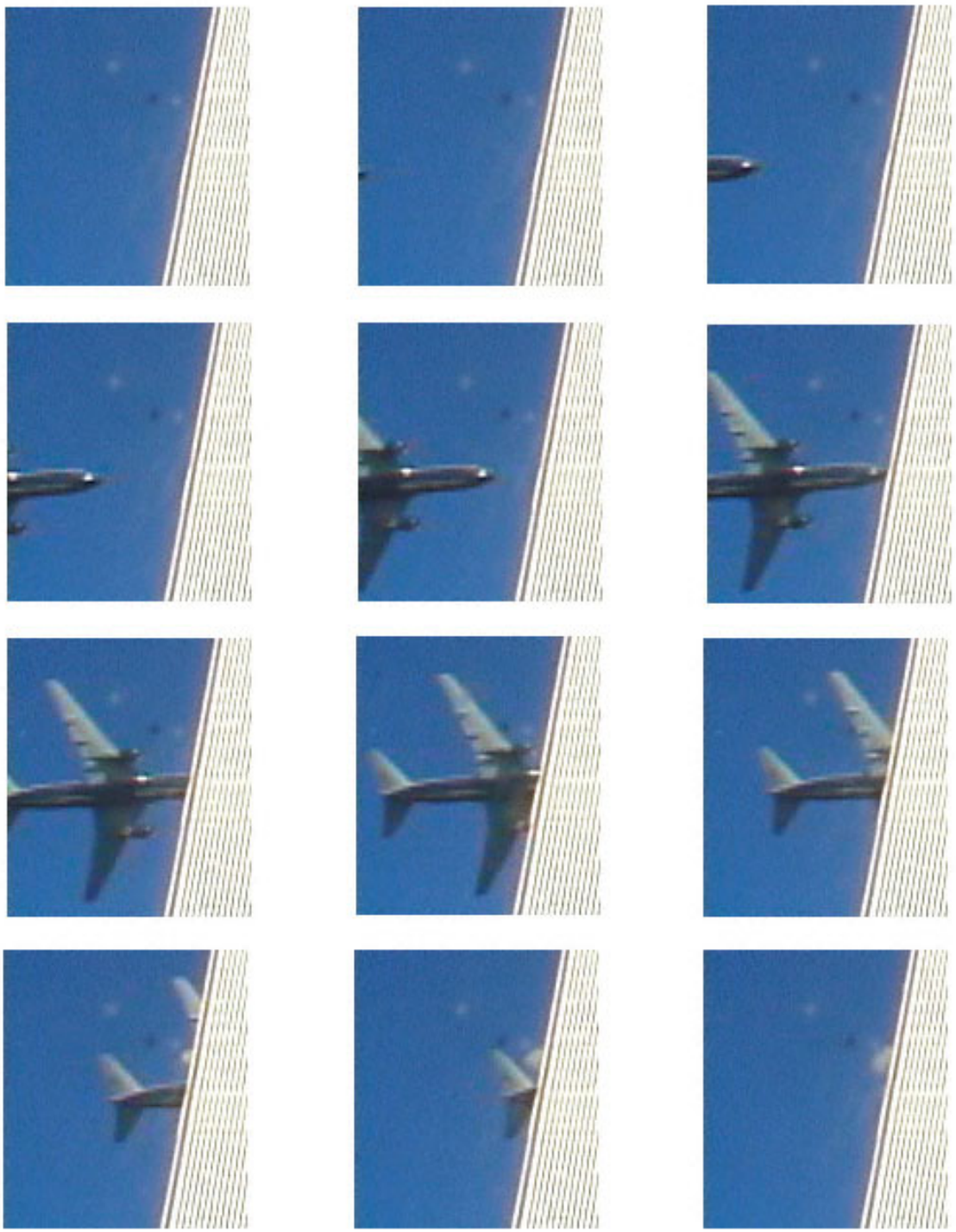


Figure H–15. Series of sequential cropped frames taken from a video shot on September 11, 2001, showing the plane approaching WTC 2. The frames, ordered from left to right and top to bottom, are separated by 33.3 ms.

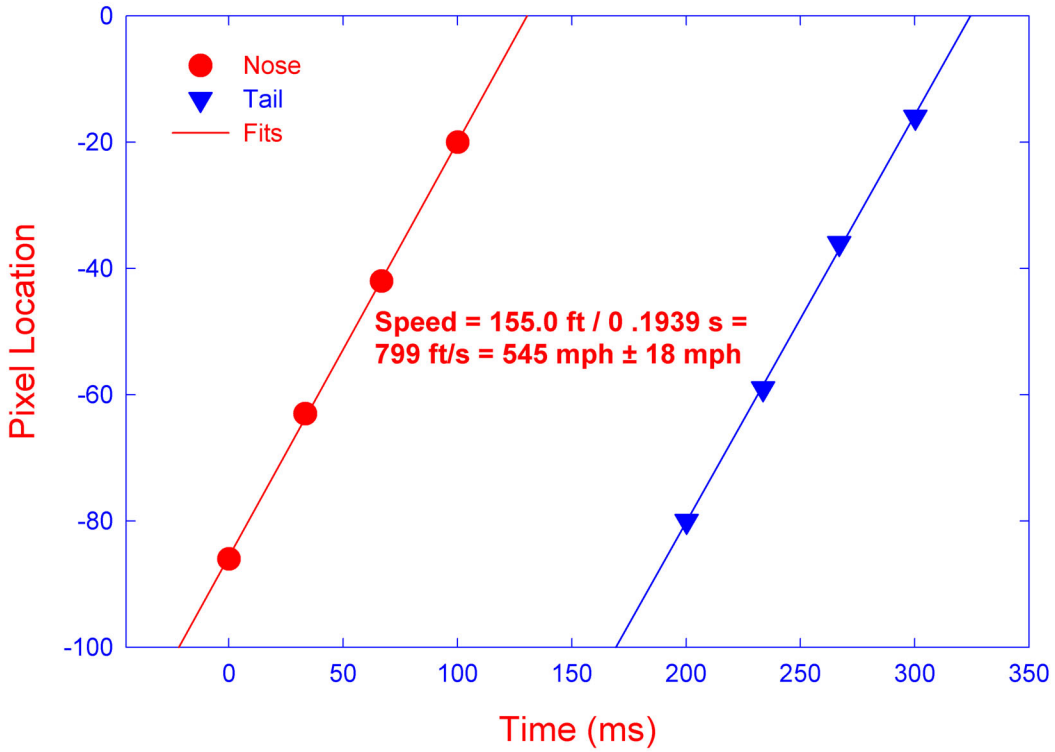


Figure H–16. Plots of pixel locations for the nose and tail of the plane that struck WTC 2 as a function of time taken from the images shown in Fig. H–15. Straight lines are the results of linear least squares curve fits to the data. Extrapolation of the lines to pixel 0 allows the time for the passage of the plane to be calculated.

analysis was used to enhance this motion and estimate the period required for the building to sway through one complete cycle. This was accomplished by creating a new video in which a single frame just prior to the plane strike was subtracted from subsequent frames. In this way, small differences between images can be identified. If the image is unchanged from the initial frame, the result should be a black image, but any changes in location or color will appear in the difference video. When this approach was applied to the video, a region of windows was observed on the building that seemed to appear and disappear. Figure H–17 shows several frames of a composite video formed by overlaying half frames of the original video and the difference video. In the initial frame (time = 0.0 seconds), the plane has not yet appeared and the difference frame is black. In the next frame (time = 10.7 seconds), the plane is approaching the building. The plane is evident in the difference frame since it represents a change in the frame. WTC 2 is still dark except near the top where changes due to smoke movement are apparent. In the third frame (time = 11.3 seconds), the plane has struck the building and dramatic changes in the appearance of the building façade in the difference frame occur. Careful inspection shows what appear to be curved lines running across the face of WTC 2. These curves result from an interaction between the straight lines formed by the windows on the tower and the straight lines of picture elements that make up the detector in the digital video camera. This well-known behavior is called the moiré effect. The moiré effect also provides a sensitive approach for determining the displacement of the building. Such an analysis is in progress and will be reported at a later time.

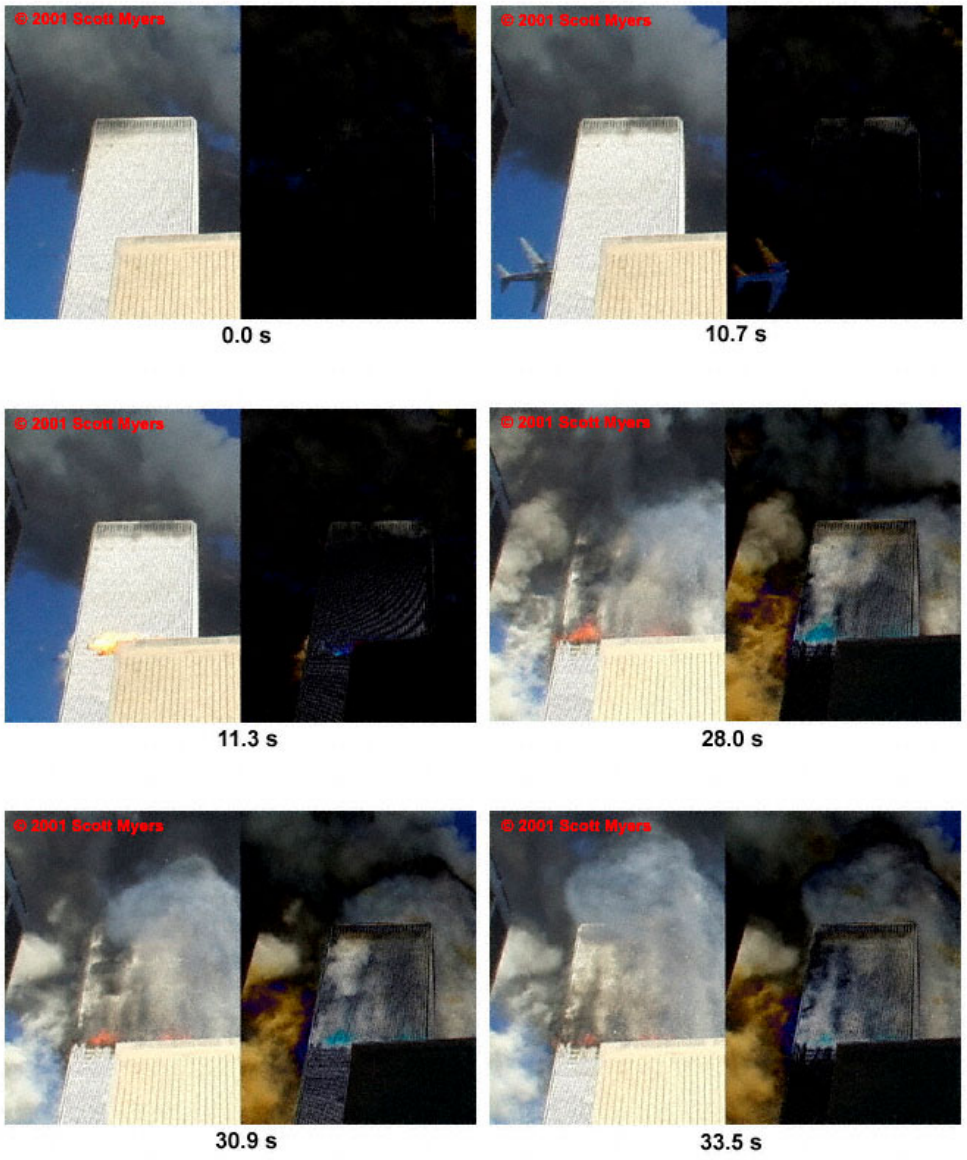


Figure H–17. Frames from a composite video are shown. The half frames on the left are taken from a video showing the plane strike on WTC 2, while the half frames on the right are generated by subtracting a frame recorded prior to the plane strike from all subsequent frames in the original video. Times refer to the period since the start of the difference video.

Following the plane strike, areas of the tower face above the strike floors become hidden by smoke, and it is difficult to see the moiré patterns in the difference frames. However, the area of the tower below the strike floors to the left of the building in the foreground continues to show a distinct difference pattern because it is not obscured by smoke. This pattern is apparent in the fifth frame (time = 30.9 seconds). On the other hand, frames 4 and 6 (times = 28.0 seconds and 33.5 seconds, respectively) have been chosen because they are near null points, and the area appears dark in the difference frame because the location of the building is essentially unchanged from its position before the plane struck. When the video is

played, the moiré patterns in this area of the tower face alternately appear and disappear in the difference video.

Because the absence of color is easiest to identify, it is straightforward to determine times when the null points occur in the difference image. Figure H–18 shows a plot of time versus null point number obtained from the difference video. The points fall on a straight line having a slope of 5.647 seconds ± 0.008 seconds (95 percent confidence interval). Because the building passes through a null point twice during a single full oscillation, the period required for a single oscillation is 11.3 seconds.

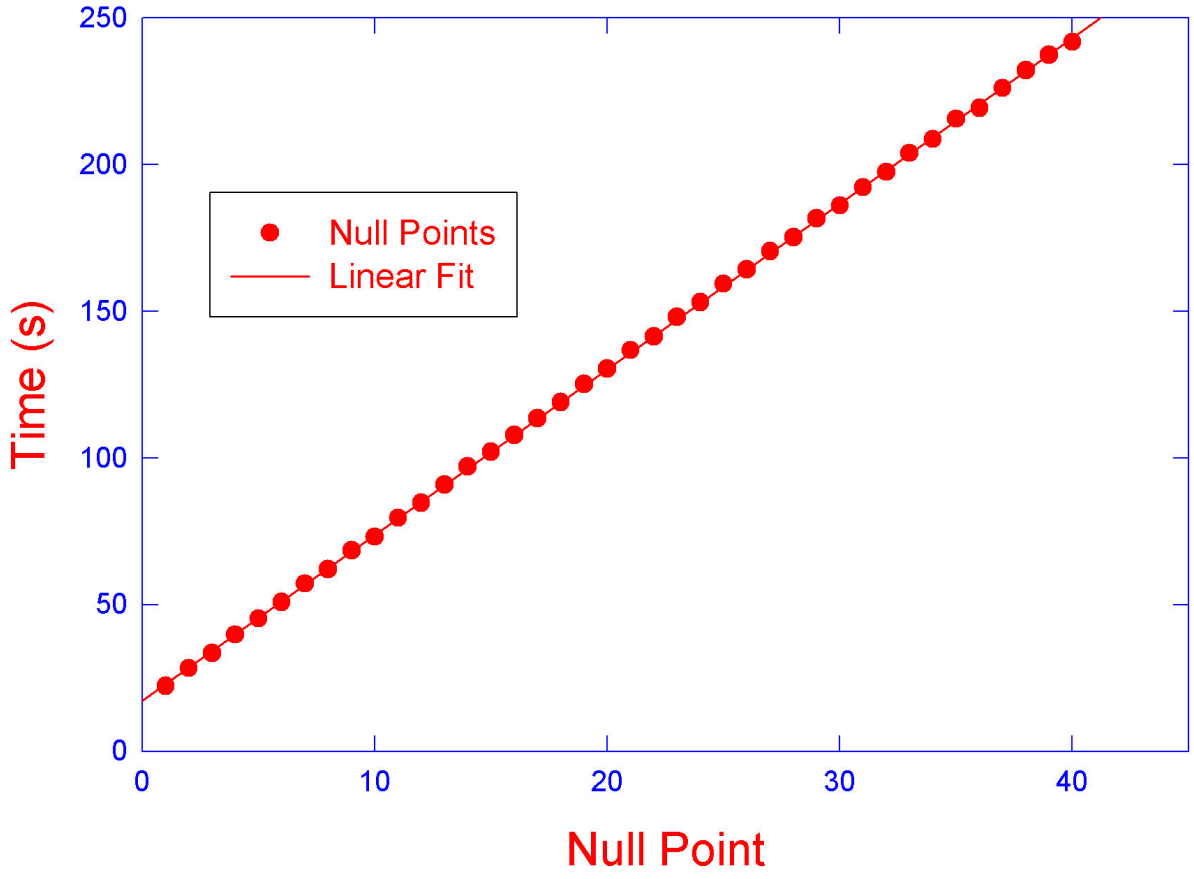


Figure H–18. The time when null points are observed in the difference video following the plane strike on WTC 2 are plotted versus the null point number. The points fall on a very good straight line having a slope of 5.647 seconds ± 0.008 seconds.

The measured oscillation period is consistent with measurements that are available from WTC 1 that yielded periods of 10.9 seconds in the east-west direction (averaged over a 9-year period that ended in 1993) and 11.6 seconds in the north-south direction (averaged over a 14-year period that also ended in 1993). The cores of the two towers were oriented perpendicular to each other so the motion monitored here should be comparable to the east-west direction of WTC 1.

Damage Resulting from the Plane Strike

The results of an analysis of the damage to the steel façade of the south face of WTC 2 are provided in Fig. H–19. Much of the steel damage pattern is revealed, but it should be noted, as indicated, that a portion of this face on the east side of the plane strike location was constantly obscured by smoke, and the detailed pattern could not be discerned. The FEMA report (McAllister 2002) also includes a figure describing the damage to the steel façade inflicted by United Airlines Flight 175. The pattern in Fig. H–19 differs somewhat from that provided in this earlier study. Some inconsistencies in façade dimensions have also been corrected in the current version.

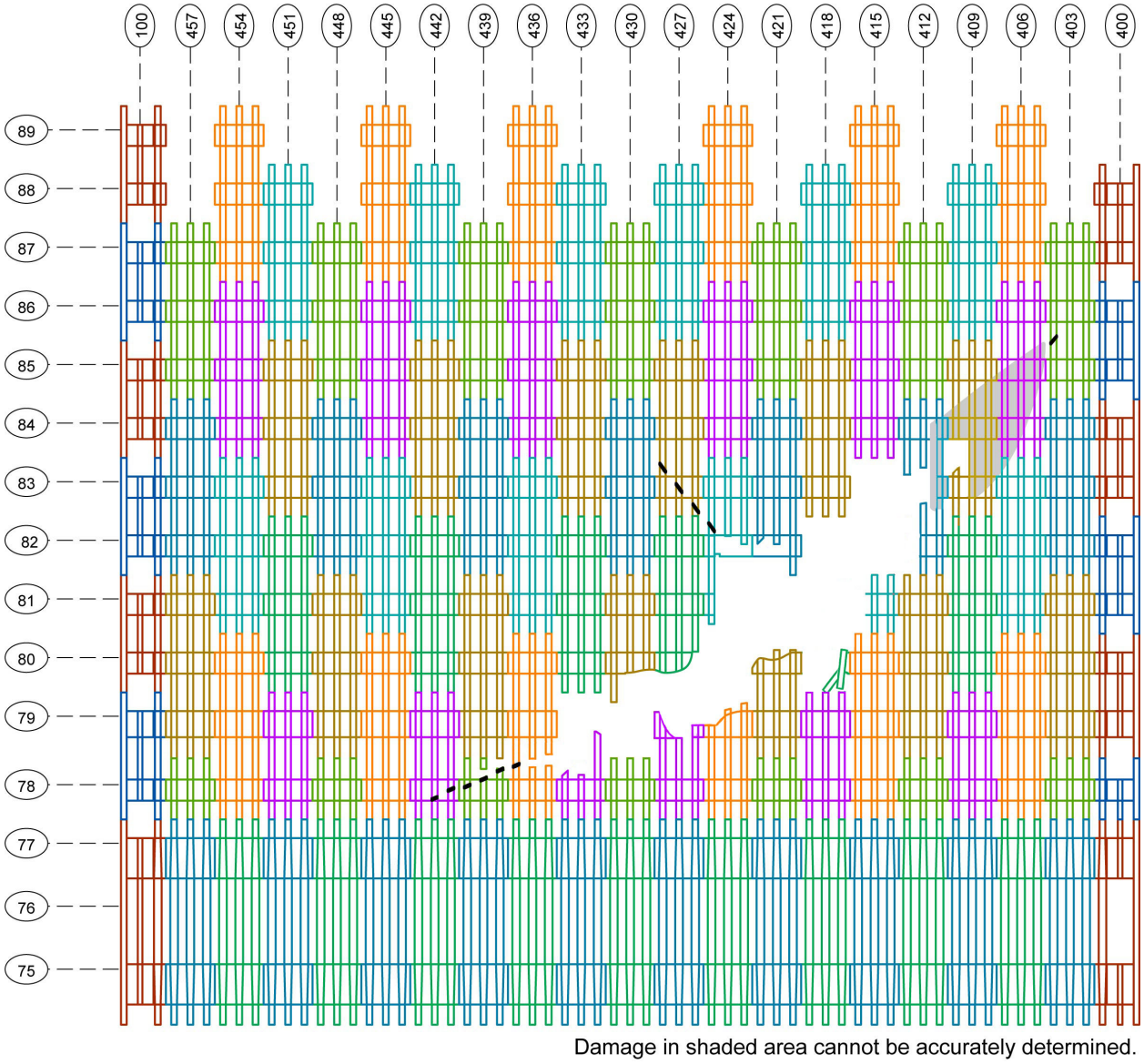


Figure H–19. A drawing of the damage to the steel facade of WTC 2. The dark dotted lines show locations where the airplane wings and tail marked the aluminum cladding on the columns. The area shaded in gray was hidden by smoke and could not be observed.

As was true for WTC 1, in areas of the façade struck by the wing tips and the upper portion of the vertical stabilizer the aluminum covering was marked, but the aluminum covers were not removed and the steel was not cut through. Measurements for the location of the left wing tip were mapped out as shown in Fig. H–19. As already noted, the area at the end of the right wing was obscured by heavy smoke. However, there were brief periods when the location of the last column struck by the wing tip could be observed. This location is indicated on column 404 of floor 95 in Fig. H–19. The center of the plane strike is clearly located towards the east side of the face. The left wing mark extends to the bottom of the spandrel located below floor 78. The actual location of the concrete floor is well above this point, which means the lowest point struck lies on floor 77. Thus, the plane strike location on WTC 2 extends from floor 77 to floor 85. This can be contrasted to the FEMA study (McAllister 2002) and most media sources that report the floors struck extended from floor 78 to floor 84.

Fireballs and Missing Windows

Intense fireballs were observed on the south, east, and north faces of WTC 2 following the plane strike. Figure H–20 compares missing windows on floor 77 to floor 86 for the four faces of WTC 2 shortly after the plane struck at 9:02:59 a.m.

The distribution of missing windows on the south face traces roughly the outline of the plane strike, with missing windows increasing in height from left to right. Recall that a portion of the east side of this face could not be observed due to smoke obscuration. The analysis indicates that a very large number of windows were removed on the east face by the collision and subsequent fireball. This is particularly true on floor 80 to floor 82. Photographs and videos show that extensive areas of the aluminum covering the façade and holding windows were removed, exposing the steel panels, as a result of the plane strike and fireballs. This damage is much more extensive than observed on the east face of WTC 1, consistent with the plane strike occurring closer to this face. In contrast to the extensive damage on the east face of the tower, no missing windows were found on the west face.

A large number of windows are also missing on the north face of WTC 2. A substantial area of the aluminum façade was also removed during the plane strike and subsequent fireball. The missing windows on this face almost appear to be a mirror image of the south face with damage towards the center being on lower floors than on the eastern edge. This suggests that a great deal of debris passed through the entire length of the building. This hypothesis is supported by close up images that show large piles of debris on the east side of the north face on floor 80 and floor 81, and on floor 79 near the center of the face. Figure H–21 includes a photograph showing these debris piles. Recall that piles of debris were also evident on floor 80 and floor 81 on the north side of the east face (see Fig. H–7).

H.6 FIRE BEHAVIORS IN THE TWO TOWERS

Analysis of the fire spread in the towers is ongoing as this update is being prepared, but sufficient information is available to allow some of the fire characteristics to be described.

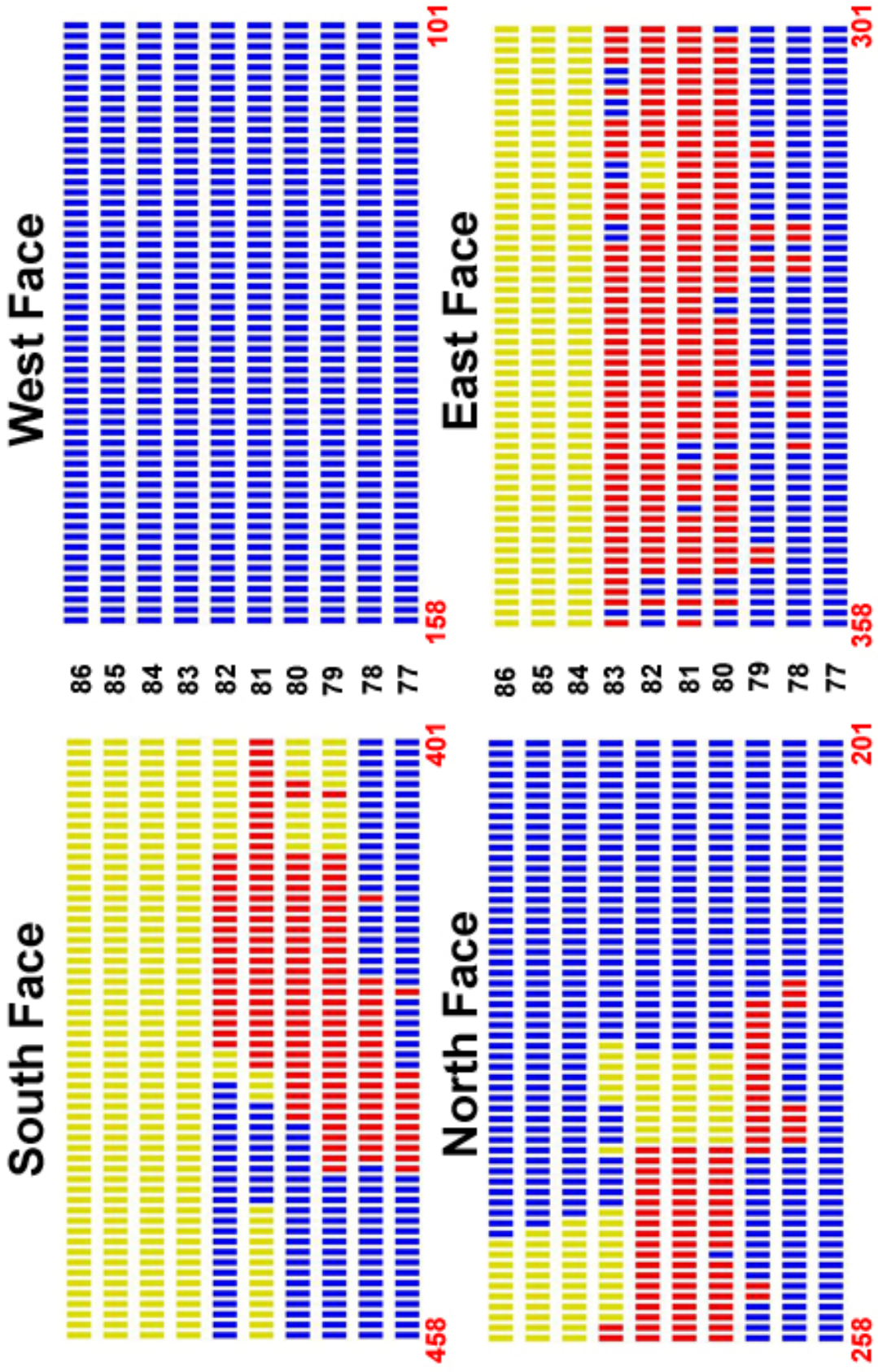


Figure H–20. The condition of windows is shown for the four faces of WTC 2 around 9:03 a.m. shortly after it was struck by United Airlines Flight 175. The colors represent ▮ - window open, ▮ - window in place, and ▮ - not visible.

Figure H–21. An enhanced photograph of the north face of WTC 2 taken at 9:58 a.m. shows the east side of the north face. Piles of debris are evident on floor 80 and floor 81 on the northeast corner and on floor 79 to the right of column 230. The "cold" area extends over floor 80 to floor 82 from roughly column 229 to 240. There is a break in column 253 on floor 81, and the adjacent column, 254, is bent. Floors 80, 81, and 82 appear to be partially collapsed. It appears as if the collapsed floor 83 in the northeast corner has broken into sections.

H.6.1 WTC 1

It has already been mentioned that substantial fireballs formed on the north, east, and south faces immediately following the plane strike. A brief period of intense burning from openings on these faces was observed after the fireballs dissipated, but in a short period (on the order of 60 seconds) the fires seemed to "damp down" and very little flame and only light smoke was evident from the outside. This period of light burning lasted several minutes before fires began to reappear.

Rapid early fire growth was observed on the east side of the north face on floor 96 and floor 97, the center of the east face on floor 94 and floor 97, and the western side of the south face on floor 96. Even though relatively little initial damage was sustained by the west face, heavy smoke followed shortly by flame appeared around window 97-437 at 8:55 a.m. After this time, a very rapid fire spread was observed across the west face on this floor. Within a couple of minutes, over half of the windows were emitting smoke, and flames were visible in many. Even though floor 92 was not directly struck by the airplane, fire appeared on the east side of the tower on this floor shortly after 9:00 a.m.

Following the initial development of large fires, fire spread continued until WTC 1 collapsed around 10:28 a.m. At times the fires displayed the systematic, relatively slow spread expected for fire growth in a typical building. For instance, after the initial rapid growth phase, fires on floors 92, 94, 96, and 97 on the east face began to move deliberately toward the south. As they spread, the fires would burn intensely at a given location for a while before dying down. As a result, these fires developed the appearance of a wave moving slowly across the building.

There were also certain times and locations during which fire appeared to spread quite rapidly. Some of these episodes were clearly connected with rapid fire growth and likely flashover in rooms. During the first half hour, significant fires were observed toward the centers of floors 92, 94, 96, and 97 on the east face that were spreading towards the north. Each of these fires eventually reached a certain point where further fire spread was inhibited for many minutes. A review of building plans showed that walls of offices or meeting rooms were presented at the locations where fire spread was inhibited.

Apparently, these walls served as effective fire breaks that protected against further fire spread. However, for each of these floors fire and smoke eventually appeared at one of the windows beyond the walls, and after one of these windows was broken fire growth was extremely rapid and robust across the remaining windows. These observations are consistent with the occurrence of flashover within an enclosed space.

At other times, unusually rapid fire growth apparently occurred in areas that are believed to have been relatively open and not constrained by walls. One of these episodes occurred around 9:54 a.m. on the north face. Fire suddenly appeared on floor 96, a location to the west of the damage inflicted by the airplane. Within a very short period of time, fire could be seen in roughly 10 windows covering a distance of more than 30 ft.

Another example of very rapid fire growth appeared to take place on floor 98. In the early period of the fire, this floor did not appear to be heavily involved, and this remained true for quite a while. However, after 9:30 a.m., fire began to appear on this floor and by 10:00 a.m., fires were observed over significant lengths on all four faces of the tower.

One of the more unusual fire spread episodes in WTC 1 occurred just after the collapse of WTC 2 around 9:59 a.m. Within a couple of minutes, a large intense fire suddenly appeared on the south side of the west face on floor 104 in an area well above any other apparent fire. This unusual jump in fire location is difficult to explain, but is likely associated with vertical shafts located in the core of the tower.

For most of the time following the plane strike, no fire was observed on any of the floors on the south face over lengths extending from the eastern edge of the tower to near the center of the face. Fires were not observed in this region of the building until around 10:00 a.m. By the time this tower collapsed roughly 25 minutes later, intense fires extending over significant lengths of the originally uninvolved area were burning on floor 94 to floor 98 in this area.

A final example of rapid fire spread and growth in WTC 1 was described previously in the *May 2003 Progress Report* for the Investigation (NIST 2003). In this case, a line of smoke appeared suddenly over a significant length of floor 92 on the north face of WTC 1 at 10:18:48 a.m., or roughly 9 minutes before the collapse of the tower. Puffs of smoke were observed simultaneously on the north face from floors 94, 95, and 97. More isolated puffs were seen at the same time from floor 92 and floor 95 on the west face and from floor 92 on the south face. Very shortly (seconds) after the appearance of the smoke, a localized fire on floor 95 to the west of the plane strike location grew very rapidly and flames erupted from windows. Following the smoke release, a large fire began to spread rapidly across the western side of floor 92 on the north face. Previous to the appearance of the smoke, only small fires were evident on this floor. By the time the tower collapsed, this fire had spread across most of the floor and had reached the western wall. This fire was responsible for the large burst of flame from the north face observed when this tower collapsed.

H.6.2 WTC 2

The fire behavior observed in WTC 2 was qualitatively different than occurred in WTC 1. Intense fireballs were created by the released jet fuel on the south, east, and north faces immediately after the airplane struck the building. As observed for WTC 1, the fireballs were followed by a brief period (on the order of a minute) of intense flaming from windows over a large area of the building. Most of these flames then "damped down" as observed in WTC 1, but two regions of intense burning remained. One of these areas was located on floor 81 and floor 82 at the northeast corner of the tower. Flames were evident from windows on either side of the corner as well as the corner itself, which had become exposed by removal of the corner facing during the plane strike. This area is in the vicinity of large piles of debris formed during the plane strike. The second fire was located primarily on floor 79 just to the left of the center (roughly from windows 79-231 to 79-238) of the north face. This is in the area of the second debris pile described earlier. Both of these fires died slowly with time when compared to fires at other locations in WTC 1 and WTC 2. Both were still burning lightly when the tower fell 56 minutes after the plane strike.

A curious aspect of the fire behavior is the existence of an area of the building façade between these two fire locations on the north face where very little fire and/or smoke was observed before the tower collapsed. This area is roughly rectangular in shape, covering floor 80 to floor 82 and extending across windows 249 to 239. Infrared images recorded shortly following the plane strike showed that this region was quite cool relative to other sections close to the fires. This area will be referred to as the "cold spot." Spreading fires seemed to move around this cold spot.

In general, the fires in WTC 2 appeared to be less active than those observed in WTC 1. The fires covered a smaller area of the façade and did not spread as quickly. This is true even when the shorter time between the plane strike and collapse for WTC 2 (1 hour 42 minutes for WTC 1 and 56 minutes for WTC 2) is taken into account. Nevertheless, there was significant fire spread, and instances of rapid fire growth similar to those seen in WTC 1 did take place.

Around 9:29 a.m., large flames and heavy smoke erupted from an area on the north face just to the right of the cold spot (around window 83-236) on floor 83. Four minutes and forty-one seconds later, flames suddenly appeared at a separate location on the same floor further to the right near window 83-226. Another area of fire formed just to the right of the cold spot on floor 82 around 9:54 a.m. or 5 minutes before the collapse. The fires on floor 79 of the north face also spread towards the west, approaching the western edge of the tower just prior to the collapse.

Initial fire growth on the east face was on floor 82. Around 9:12 a.m., flames could be seen in nearly half of the windows on this floor, and heavy smoke was pouring from additional windows. Only limited fire was evident on lower floors at this time. The fires on floor 82 grew smaller after this time, and most were no longer visible when the tower collapsed. Around 9:35 a.m., heavy flames and smoke appeared over large areas of floor 79 and floor 80. These fires abruptly died down 45 seconds later, before growing back slowly during the remainder of the time before the tower collapsed.

In the early period following the plane strike, fire growth on the south face was seen primarily on floor 81 with active fires present on both sides of the airplane strike location. Smaller isolated fires were present on other floors around the area damaged by the airplane. These fires were relatively quiet and stationary until just prior to the collapse. At 9:56 a.m., there was a sudden release of smoke along much of floor 80 extending from the area of the plane strike to near the western edge. During the next 2 minutes, an intense fire developed covering approximately windows 81-441 to 81-454.

No smoke or fire was observed near the floors struck by the airplane on the west face of WTC 2. Some smoke was apparent at windows higher on the face. This was most likely coming from windows broken by occupants located on these floors.

H.7 EVIDENCE FOR COLLAPSED FLOORS IN WTC 2

H.7.1 Hanging Objects

In the *May 2003 Investigation Progress Report* (NIST 2003), a photograph was shown in which there appeared to be a floor draped across a number of windows extending roughly from 310 to 342 across the east face of floor 82 of WTC 2. Figure H–22 compares an image taken shortly after the plane strike at 9:03 a.m. and one taken at 9:55 a.m. shortly before the tower collapsed. At the earlier time, the hanging object is already present, but is seen through the windows draped much higher on the floor 82. An interpretation consistent with these observations is that floor 83 along the east side of WTC 2 was partially collapsed over a significant fraction of its length by the passage of the plane through the building. At the later time the floor has sagged further. By reviewing a number of photographs and videos, it has been determined that the change in floor position occurred between 9:34 a.m. and 9:38 a.m.

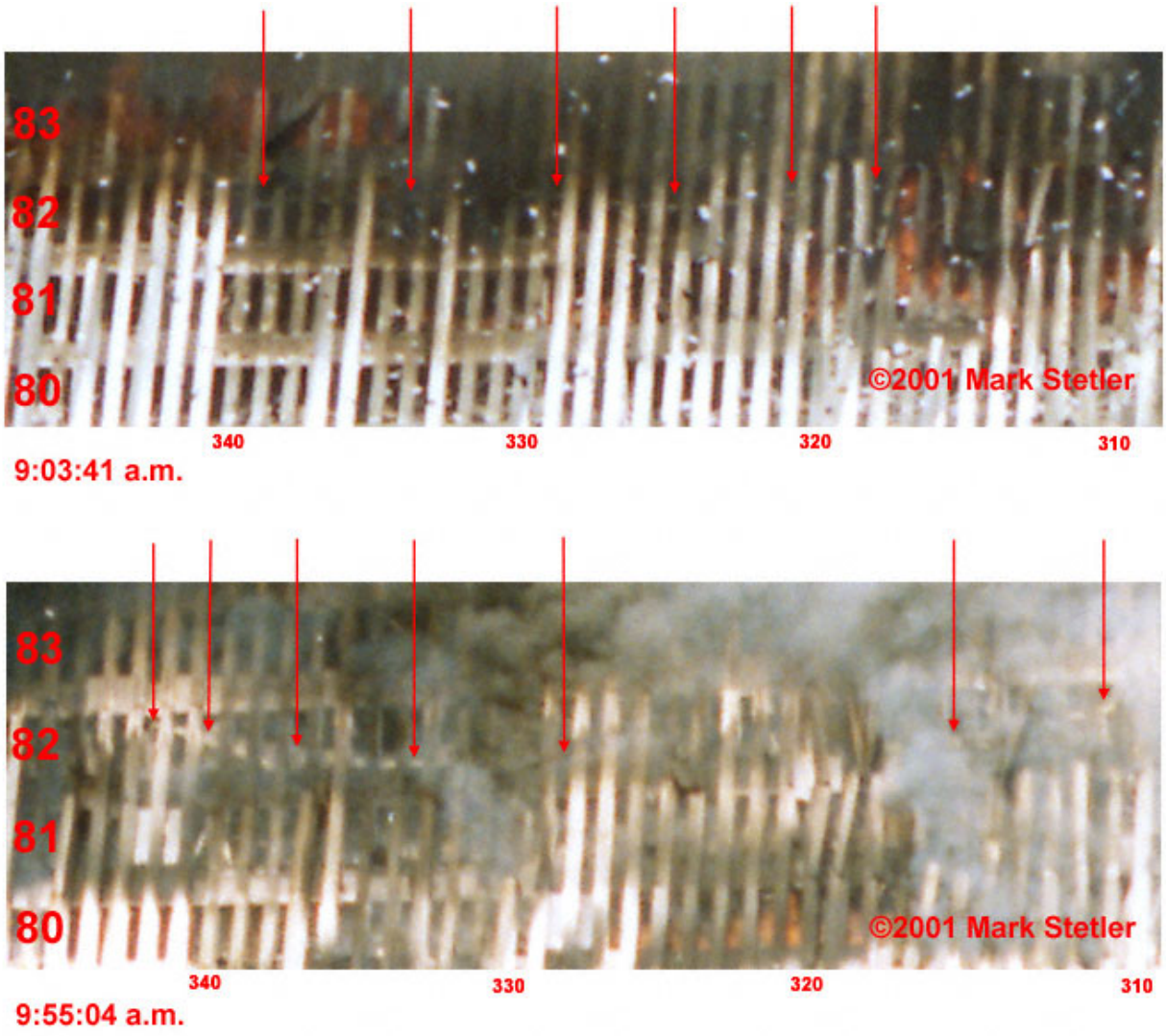


Figure H–22. Images of the east face of WTC 2 taken shortly after the plane struck and shortly before the tower collapse are shown. An object that is most likely a floor can be seen through windows on floor 82 as indicated by the arrows. The object has dropped lower between the times the two photographs were taken.

Very similar objects, albeit of shorter length, are seen hanging in windows in images taken from the north. These objects are apparent in Fig. H–21 hanging below floors 81, 82, and 83. As seen through windows on floor 82 (corresponding to the floor 83), the floor appears to have split into at least two sections.

H.7.2 Molten Material

It has been reported in the FEMA report (McAllister 2002) as well as in the media that what appeared to be molten metal was observed pouring from the north face near the northeast corner. This is the area where the sustained fires were seen. Video records and photographs indicate that the material first

appeared at 9:51:52 a.m. and continued to pour intermittently from the building until the time of collapse. Some of the material can be seen falling in Fig. H–21. Close-up video and photographs of the area where the material is pouring from have been examined and show that it is falling from near the top of window 80-256. The most likely explanation for this observation is that the material had originally pooled on the floor above, that is, floor 81, and that it was allowed to pour out of the building when this floor either pulled away from the outer spandrel or sank down to the point where the window was exposed. The fact that the material appears intermittently over a several minute period suggests that the floor was giving way bit by bit.

The composition of the flowing material can only be the subject of speculation, but its behavior is consistent with it being molten aluminum. Visual evidence suggests that significant wreckage from the plane passed through the building and came to rest in the northeast corner of the tower in the vicinity of the location where the material is observed. Much of the structure of the Boeing 767 is formed from two aluminum alloys that have been identified as 2024 and 7075 and closely related alloys. These alloys do not melt at a single temperature, but melt over a temperature range from the lower end of the range to the upper as the fraction of liquid increases. The Aluminum Association handbook (Aluminum Association 2003) lists the melting point ranges for the alloys as roughly 500 °C to 638 °C and 475 °C to 635 °C for alloys 2024 and 7075, respectively. These temperatures are well below those characteristic of fully developed fires (ca. 1,000 °C), and any aluminum present is likely to be at least partially melted by the intense fires in the area.

H.8 PROGRESS ON COLLECTION OF IMAGES AND ANALYSIS FOR WTC 7

Visual material is also required to characterize the initial damage to, fire spread in, and collapse behavior of WTC 7. Considerable useful material has been collected, but the visual record for times between the collapses of WTC 1 and WTC 7 is much less complete than those for the two towers. The reasons for this are easy to understand. Following the collapses of the towers, most people were focused on escape or rescue. A large dust cloud was formed by the collapses, and fires developed that generated large amounts of smoke. Both tended to obscure views of WTC 7, particularly from the south due to the northwesterly wind direction on September 11, 2001.

Both photographs and videos have been included in the database that show fires and damage to the east, north, and west faces of WTC 7. Some of this material has been timed, but in general the record is insufficient to allow generation of a complete time line of fire behavior for the relevant period. Numerous images show the upper portion of WTC 7 from the south, but the actual face of the building is generally obscured by smoke. No clear images of the lower portion of the south face have been obtained despite a careful search and repeated appeals for the public's help. This is particularly unfortunate since most of the damage caused by the collapses of the towers, and particularly WTC 1, should have occurred on this face.

There is considerable interest in images showing the collapse of WTC 7. Currently, there are at least four videos in the database that include the collapse, primarily from northerly directions, as well as several photographs. While not ideal, these are providing adequate information for characterizing the collapse sequence, and some progress along these lines has been made.

An effort has begun to map out the same information concerning fires, smoke, and windows as in the towers using visual material in the database. This effort will continue with a goal of mapping out as much of the fire time line as possible based on the material in the database.

H.9 SUMMARY WITH KEY FINDINGS

This section provides a brief summary of progress on the collection and analysis of visual data along with key findings.

The approaches used to identify and obtain visual material related to the WTC disaster are described along with the approaches employed by NIST to archive and catalog the material. Material is either saved in its original digital format or digitized and saved, and a commercial software package has been used to provide data entry, a searchable database, and ready access to assets for review. The large numbers of attributes used to characterize the photographs and videos are included.

Separate databases are provided for photographic and video materials. A major effort has focused on assigning accurate times to the material, and the approaches used are summarized. In excess of 6,700 photographs and 6,900 video clips have been included in the databases and 45 percent and 39 percent, respectively, of these have assigned times accurate to 3 seconds or better.

Major events timed to an accuracy of 1 second are:

- First plane strike on WTC 1: 8:46:30 a.m.
- Second plane strike on WTC 2: 9:02:59 a.m.
- Collapse of WTC 2: 9:58:59 a.m.
- Collapse of WTC 1: 10:28:25 a.m.
- Collapse of WTC 7: 5:20:52 p.m.

An approach has been developed to characterize the observed fire behaviors at the periphery of the buildings on a window-by-window basis by determining whether windows are open or closed and whether smoke and/or fire are observed. If smoke is present, it is characterized as “light” or “heavy”, and fires are characterized as “spot” (a small local fire), “fire inside,” and “external flaming.” The observations are coded in separate electronic spreadsheets for each building, façade, and time.

Two approaches are used to visualize the fire-related parameters. The first is a Web-based application that displays single sides of the towers at a single time. The second is a time-dependent three-dimensional representation based on Smokeview (Forney and McGrattan 2003; Forney, Madrzykowski, McGrattan, and Sheppard 2003).

Photographs and videos have been used to characterize several aspects related to the plane strikes on the towers and the distribution of damage on the external faces. For WTC 1, locations where the ends of the wings and vertical stabilizer of the tail section struck the north face and the damage to the steel façade are mapped. The behavior of fireballs generated by the release of fuel as a result of the collision of the

aircraft with the tower and initial tower damage as reflected in broken windows is used to characterize the distribution of damage to the facades of the tower. In addition, it has been shown that an exterior panel section from the south face was dislodged and landed on the ground. It contained an aircraft wheel that passed through the tower.

The following conclusions are reached concerning the immediate effects of the plane strike on WTC 1:

- The airplane struck columns on the north face ranging from 109 to 152 and covering floor 93 to floor 99.
- Damage and initial fire growth were greater on the east face of the tower than on the west. Significant damage and early fire growth occurred on the west side of the south face, but not on the east side.
- A three-story panel section was knocked from the south side of the tower and had an aircraft wheel lodged in window 95-329.

Visual evidence related to the plane strike on the south face of WTC 2 is more extensive than for WTC 1. This has allowed additional analyses beyond the mapping of damage on the plane strike face and façade damage to the remaining faces. The following conclusions have been reached concerning the immediate effects of the plane strike on WTC 2:

- The aircraft struck the tower with a measured speed of 545 miles per hour ± 18 miles per hour.
- The collision of the aircraft caused a measurable sway of the tower that lasted more than 4 minutes. The period of oscillation was 11.3 seconds.
- The airplane struck columns on the south face ranging from 404 to 443 and covering floor 77 to floor 85.
- Large areas of the façade were removed and/or damaged along the east face of the tower and on the eastern side of the north face. No façade damage or window breakage was evident on the west face.
- Debris piles are observed in the northeast corner of the tower primarily on floors 80 and 81. Debris is also evident towards the center of the north face on the floor 79.
- Column 253 on the north face is broken on the floor 81 and the column 254 is severely distorted.

Detailed maps for fire behavior are currently being made. This update characterizes general fire behaviors for the two towers and notes some particularly interesting observations. For WTC 1, the following observations are highlighted.

- Extensive fires observed immediately following the plane strikes and which are most likely associated with released jet fuel damped down after roughly 60 seconds.

- In the period following the plane strikes fires tended to reappear over a period of many minutes. Initial fire growth was principally observed on floor 96 and floor 97 on the north face, floor 94 and floor 97 on the east face, floor 96 on the south face, and floor 97 on the west face.

- Observed fire spread rates were quite variable. Examples of both relatively slow and very rapid apparent fire spread are described.

- Interior walls at several locations were inferred to protect areas of the towers for a period of many minutes, though they were typically eventually breached by nearby fires.

- Following the collapse of WTC 2, a large fire appeared and grew rapidly on the west face at floor 104.

- There was an extensive area of the façade on the eastern side of the south face for which no fire was observed until at least 1 hour following the plane strike. When fires finally did appear in this area their growth was rapid over multiple floors.

- A large amount of smoke was suddenly released from floor 92 on the north face at 10:18:40 a.m. Smoke was expelled simultaneously from other floors and faces. Immediately after the smoke release rapid fire growth was observed at an isolated location on floor 95 and across much of the west side of the north face on floor 92.

Observed fire behaviors for WTC 2 were somewhat different than for WTC 1. This is true even when the differences in times between plane strikes and collapses (1 hour and 42 minutes for WTC 1 and 56 minutes for WTC 2) are considered. The following observations concerning fire behavior in WTC 2 are emphasized:

- Extensive fires observed immediately following the plane strikes and most likely associated with released jet fuel damped down after roughly 60 seconds.

- Two regions of intense fire remained following the initial fire period due to jet fuel burning. These fires were located on floor 81 and floor 82 in the northeast corner and towards the center of the north face on floor 79. These fires burned for longer periods than observed elsewhere in WTC 1 and WTC 2. They are located in regions of the tower where debris piles are observed.

- No large fires were observed in a multi-floor region on the north face located between the two fire areas described in the last bullet.

- Initial fire growth in areas away from the sustained fires was along the east face of floor 82. Large fires did not appear on lower floors of this face until later and were sporadic in space and time.

- Prior to the tower collapse, fire spread primarily from east to west was observed on floors 79, 82, and 83 of the north face.

- A sudden release of smoke from windows on the west side of the south face on floor 80 occurred at 9:56:37 a.m. This was followed very shortly by the appearance of heavy fire.

A number of photographs and videos show what appears to be floor 83 hanging across window openings over a large fraction of floor 82 on the east face of WTC 2. This object is observed very shortly after the plane strike and is found to drop lower prior to the tower collapse. On the north face, shorter lengths of what appear to be floors 81, 82, and 83 are seen hanging through the windows below.

Starting around 9:52 a.m., a molten material began to pour from the top of window 80-256 on the north face of WTC 2. The material appears intermittently until the tower collapses at 9:58:59 a.m. The observation of piles of debris in this area combined with the melting point behaviors of the primary aluminum alloys used in the Boeing 767 suggest that the material is molten aluminum derived from aircraft debris located on floor 81.

The visual record for the period following the collapses of the two towers is much less complete than prior to this time. In addition to the general chaos caused by the collapses, significant dust and smoke from fires started by the collapses obscured the site. As a result, it has not been possible to identify clear visual images showing the damage to the south face of WTC 7 caused by the collapses of WTC 1 and WTC 2. The number of videos and photographs showing fires on the east, north, and west faces of WTC 7 is limited and sporadic. The images that are available are being used to generate an approximate time line for fire growth and spread.

H.10 REFERENCES

Forney, G. P., and K. B. McGrattan. 2003. *User's Guide for Smokeview Version 3.1*: A Tool for Visualizing Fire Dynamics Simulation Data. NISTIR 6980. National Institute of Standards and Technology. Gaithersburg, MD.

Forney, G. P., D. Madrzykowski, K. B. McGrattan, and L. Sheppard. 2003. Understanding fire and smoke flow through modeling and visualization, *IEEE Computer Graphics and Applications*, vol. 23, p. 6-13.

McAllister, T., ed. 2002. *World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations*. FEMA 403. Federal Emergency Management Agency. Washington, DC, May.

NIST (National Institute of Standards and Technology). 2003. *May 2003 Progress Report on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster*. NIST Special Publication 1000-3. U.S. Department of Commerce, Washington, DC, May.

The Aluminum Association. 2003. Aluminum Standards and Data - 2003. The Aluminum Association, Inc., Washington, DC.

This page intentionally left blank.